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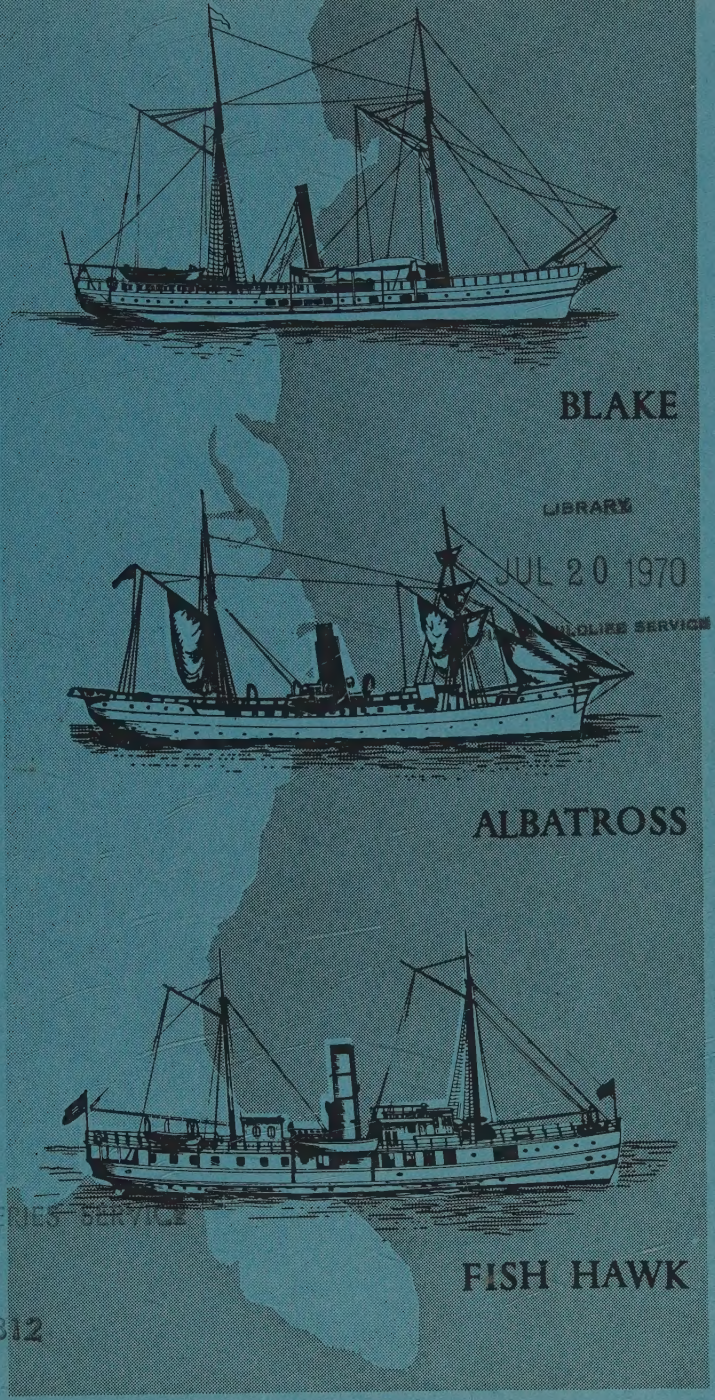

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Bureau of Commercial Fisheries

FISHERY BULLETIN

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As the Nation's principal conservation agency, the Department of the Interior has basic responsibilities for water, fish, wildlife, mineral, land, park, and recreational resources. Indian and Territorial affairs are other major concerns of America's "Department of Natural Resources."

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SUPERSATURATION OF NITROGEN IN THE COLUMBIA RIVER AND ITS EFFECT ON SALMON AND STEELHEAD TROUT

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ABSTRACT

The nitrogen gas regime in the Columbia River was studied in 1966 (from Grand Coulee Dam, Wash., to the estuary at Astoria, Oreg.) and in 1967 (from Priest Rapids Dam, Wash., to the estuary). Dissolved nitrogen was subject to considerable seasonal fluctuation and varied with flow of water over spillways of dams; it was normal (near 100-percent saturation) in the fall and winter when no water was spilled, and high (above 135-percent saturation) in the spring and summer when large volumes of water were spilled. Some saturation levels over large areas were high enough and lasted long enough to be potentially dangerous to salmon (*Oncorhynchus* spp.) and steelhead trout (*Salmo gairdneri*).

Supersaturation of nitrogen at Priest Rapids Dam lowered the tolerance of juvenile fish to temperature increases, and some showed symptoms of gas bubble disease. Field studies to determine the effects of high levels of dissolved nitrogen on adult salmon and steelhead trout did not provide conclusive results.

Observations in the spring of 1965 by the Washington State Department of Fisheries and the Bureau of Commercial Fisheries showed that saturation of dissolved nitrogen at some sites in the Columbia River was as high as 125 percent. Because levels of this magnitude had produced gas bubble disease in adult and juvenile salmon (Rucker and Hodgeboom, 1953; Harvey and Cooper, 1962; and Westgard, 1964), additional surveys were made in 1966–67 to attempt to determine whether high levels of dissolved nitrogen might be responsible for losses of adult salmon and poor production of young fish at spawning channels.

The first phase in the study of nitrogen and oxygen concentrations (February–November 1966) was primarily to determine the cause of supersaturation of dissolved nitrogen and to determine seasonal variations. Water samples were taken from 26 sites between Grand Coulee Dam, Wash., near the Canadian border, and Astoria, Oreg., at the mouth of the river. The second phase (March–October 1967) was to determine the effect of nitrogen supersaturation on adult and juvenile salmon. We suspected that gas bubble disease was one of the factors in losses of adult and juvenile chinook salmon (*O. tshawytscha*) migrating between dams. The studies in 1967 concentrated on obtaining field evidence of such losses.

This report discusses the amounts of dissolved nitrogen in 1966–67, the effect of dams and reservoirs on saturation, the seasonal variation and duration of supersaturation, and the effect of supersaturation of nitrogen on juvenile and adult salmon and steelhead trout (*Salmo gairdneri*) in the Columbia River.

METHODS

Descriptions of the sampling stations, analytical techniques, and other experimental procedures are given in this section.

SAMPLING STATIONS AND TECHNIQUE

Twenty-six principal sampling stations were established along the Columbia River between the forebay of Grand Coulee Dam and the estuary at Astoria (fig. 1). All stations except 13, 25, and 26 were either in midreservoir, about 500 m. upstream from the dam, or on the spillway side of the river, about 500 m. below. Samples of water were taken at the surface and at 10-m. depths at the forebay stations. The spillways discharge from the surface down to a maximum depth of about 10½ m., and

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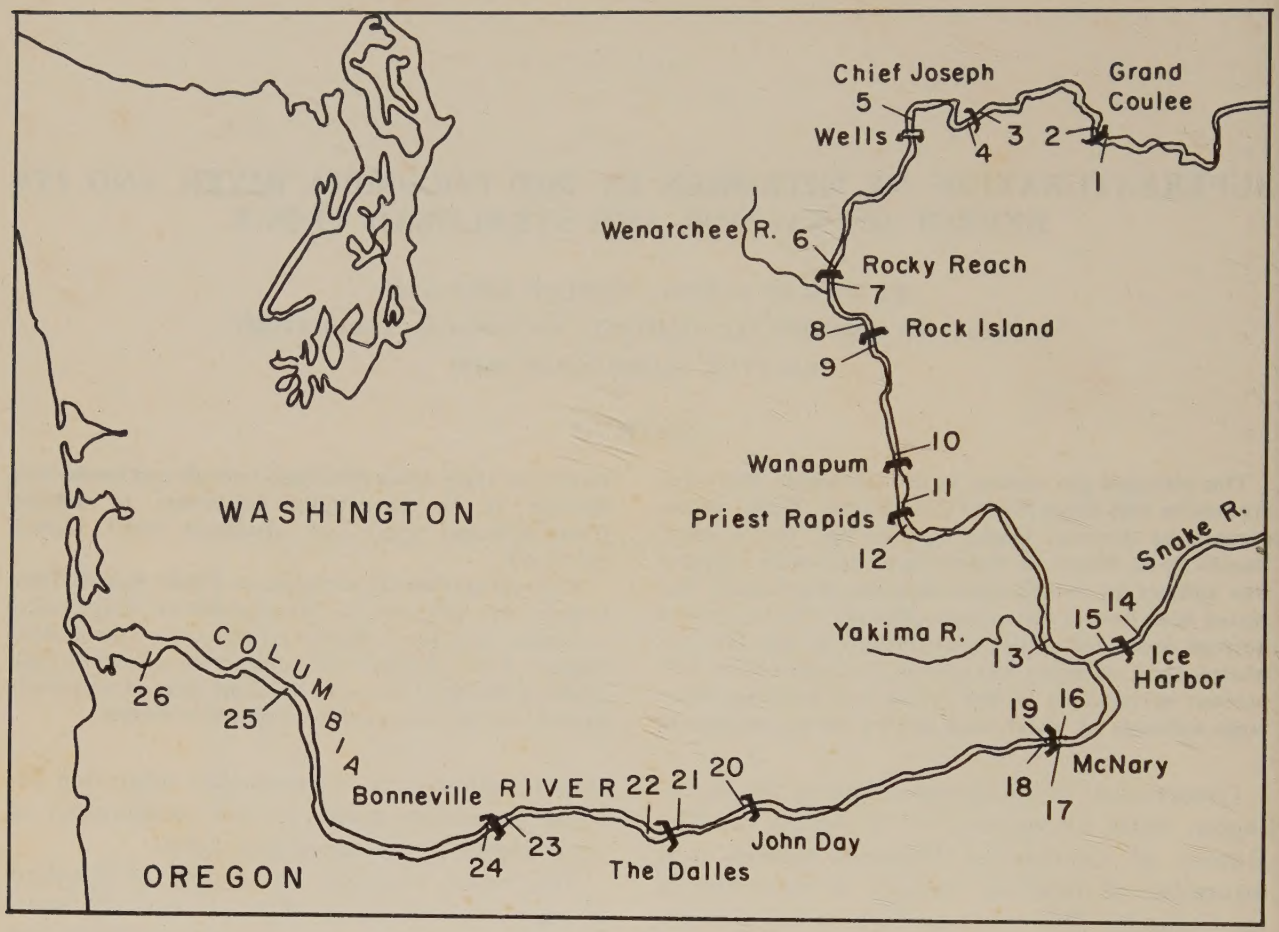

FIGURE 1.—Principal sampling stations on the Columbia and Snake Rivers.

the turbines withdraw water from about 8 m. down to 20 m. at all the dams downstream from Chief Joseph Dam. Maximum forebay depths at full pool do not exceed 45 m. Because of these facts and the fact that temperatures in the forebay of the reservoirs seldom varied more than 1° C. from the surface to the bottom, a sample at the surface and 10-m. depth was sufficient to represent the average forebay concentration and in turn represent the water passing through the turbines and spillways. Duplicate samples were collected at the surface at stations below the dams where high current velocities made it impossible to sample at depth. Because the amount of soluble nitrogen depends on water temperature,[1] the temperature of each sample was recorded before it was placed in an iced cooler for transport to the laboratory. The use of two aircraft made it possible to obtain all samples in 1 day; analysis was completed on the following day.

Water samples were obtained from additional stations when more information was needed for a specific dam or reservoir. For example, additional stations were established along the reservoirs behind McNary and Chief Joseph Dams to study changes in nitrogen content of water passing through these reservoirs. Additional stations were also sampled when the effect of a specific dam on saturation levels was examined. Table 1 gives a detailed description of the principal sampling stations and the dates when samples were obtained.

ANALYSIS

The amount of dissolved nitrogen in the sample was determined by a modification of the technique used by Swinnerton, Linnenbom, and Cheek (1962). A Fisher blood gas analyzer Model

[1] An atmospheric pressure of 760 mm. mercury was used in computing normal saturation (100 percent) for each sample.

TABLE 1.—*Locations and dates of sampling in the Columbia and Snake Rivers; sampling sites are shown by number in figure 1*

Station location and number		Dates sampled																						
		1966											1967											
		Feb.	Mar.	Apr.		May	June	July	Aug.	Sept.	Oct.	Nov.	Apr.	May		June		July		Aug.		Sept.	Oct.
		9	7	6	18	9	6	11	1	6	2	7	3	1	15	6	27	5	19	2	23	5	3
Number	*Station*																							
1	Forebay—Grand Coulee Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
2	Tailrace—Grand Coulee Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
3	Forebay—Chief Joseph Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
4	Tailrace—Chief Joseph Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
5	Wells damsite	X	X	X	X	X	X	X	X	X	X	X	----											
6	Forebay—Rocky Reach Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
7	Tailrace—Rocky Reach Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
8	Forebay—Rock Island Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
9	Tailrace—Rock Island Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
10	Forebay—Wanapum Dam.	X	X	X	X	X	X	X	X	X	X	X	----											
11	Forebay—Priest Rapids Dam.	X	X	X	X	X	X	X	X	X	X	X	----			X	X	X	X	----	X	----		
12	Tailrace—Priest Rapids Dam.	X	X	X	X	X	X	X	X	X	X	X	----			X	X	X	X	----				
13	Columbia River at Richland, Wash.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
14	Forebay—Ice Harbor Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	----	X	----	X	X	
15	Tailrace—Ice Harbor Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	----					
16	Forebay—McNary Dam (north side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
17	Forebay—McNary Dam (south side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
18	Tailrace—McNary Dam (south side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
19	Tailrace—McNary Dam (north side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
20	John Day damsite	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
21	Forebay—The Dalles Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
22	Tailrace—The Dalles Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
23	Forebay—Bonneville Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	----	
24	Tailrace—Bonneville Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	----	
25	Columbia River at Longview, Wash.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
26	Columbia River estuary Astoria, Oreg.	X	X	X	X	X	X	X	X	X	X	X	X	----										

6–390V2 [2] was substituted for their Model 25, and the length of the extraction chamber was increased to 150 mm. Model 6–390V2 is more sensitive than Model 25, and the longer extraction chamber allowed analysis of larger samples.

Saturation values quoted in this report are correct to within ±2 percent. Limitations in the accuracy of the method and the uncertainty of the theoretical solubilities of nitrogen precluded more precise interpretation.

[2] Trade names referred to in this publication do not imply endorsement of commercial products by the Bureau of Commercial Fisheries.

EFFECT OF DAMS AND RESERVOIRS ON SATURATION OF DISSOLVED NITROGEN

Major causes of supersaturation of water with gases are heavy concentrations of algae (Woodbury, 1942), warming of water without adequate circulation and exposure to the atmosphere for equilibration, and falling of water into an enclosed plunge basin (Harvey and Cooper, 1962). Algae concentrations like those described by Woodbury are not found in the Columbia River and the river is not warmed sufficiently at any location to account for the high concentrations previously recorded. Spillways at dams create

conditions similar to those described by Harvey and Cooper and were suspected to be the major cause of supersaturation; during periods of high flow, large volumes of water plunge from spillways at all the dams on the Columbia River into various types of basins.

OBSERVATIONS AT DAMS

Samples analyzed at individual dams to determine the effect of turbines and spillways on dissolved nitrogen indicated that supersaturation in the Columbia River is caused primarily by spillways. This was clearly demonstrated during tests at Bonneville Dam in March 1966 when the Corps of Engineers spilled large volumes of water at a time when spilling normally does not occur. Variables, such as spilling at upstream dams and rapid temperature increases, were eliminated; the only factor which remained that could create supersaturation was the spilling of the water. The concentration of dissolved nitrogen at Bonneville Dam before and during these spillway tests is shown in figure 2. Two replicates of samples were taken before spill and three replicates after spill at each location. Maximum variance in analysis at each location before spill was 4 percent; after spill, 6 percent. Concentrations in the forebay and below the turbines and spillway before the spill tests were near normal saturation (98–102 percent). During the spill tests, concentrations below the spill increased to 125-percent saturation, whereas concentrations in the forebay and below the turbines remained near 100 percent.

Nitrogen levels at other dams (table 2) indicated that each dam has different, characteristic effects on nitrogen saturation. The spillways at Bonneville, Grand Coulee, and Ice Harbor Dams increased the concentration of nitrogen, but the amount of the increase differed. By contrast, the spillway at Priest Rapids decreased the concentration when the water was supersaturated above the dam. Differences in the structural arrangement of the dams, shape of the spillways, and depth of tailwater are factors which could explain the differences.

EQUILIBRATION IN RESERVOIRS

Sampling throughout the length of reservoirs above Chief Joseph and McNary Dams showed that water supersaturated with dissolved nitrogen does not equilibrate during transit. In McNary Reservoir on June 8, the saturation of nitrogen that entered the reservoir from the Columbia River averaged 127 percent; samples collected in the forebay of McNary Dam on the same day averaged 127 percent. Evidently, lack of circulation and warming of the surface water in the forebay tended to maintain the saturation level.

TABLE 2.—*Average nitrogen concentrations (percentage saturation) in the Columbia River of samples taken at specific dams to determine effect of dams on water passing through turbines and over spillways (spring 1966)*

Location and date	Forebay above spill	Tailwater below spill	Forebay above turbines	Tailwater below turbines	Samples	Spill volume
	Percent	*Percent*	*Percent*	*Percent*	*Number*	*100 c.m.s.*
Bonneville: Mar. 10 and 11	102	125	94	98	8	28.3–42.5
The Dalles: Feb. 27–Mar. 2	103	104	102	97	12	1–33.7
Ice Harbor: May 16 and 18	109	118	107	105	8	.5–0.8
Priest Rapids: May 25 and 31	131	114	121	----------	8	1.9–2.4
Grand Coulee: Apr. 27	105	129	105	105	4	.7

SEASONAL AND DAILY VARIATIONS IN SATURATION OF DISSOLVED NITROGEN

As expected, variations of dissolved nitrogen concentrations from Grand Coulee Dam to the estuary depended largely on the volume of water released over the spillways. Nitrogen saturation in February, March, and April of 1966 was below 110 percent except below dams where intermittent spilling occurred. On February 9, when no dams were spilling (table 3), all samples had saturation below 105 percent (fig. 3). The concentrations in March were nearly the same except below the Bonneville spillway where spilling was minimal. Saturation of dissolved nitrogen remained below 110 percent through April except in areas of spilling. Streams began to rise in April, and spill releases became regular at all dams by early May. Surface concentrations of nitrogen were over 110 percent at all stations except in the forebay of Grand Coulee and The Dalles Dams. The highest concentration in May (132 percent) was downstream from the spillway at Bonneville Dam. Temperature on May 9 ranged from a low of 8.5° C. (47.3° F.) in the forebay of Chief Joseph Dam to a high of 15.3° C. (59.5° F.) in the forebay of Grand Coulee Dam.

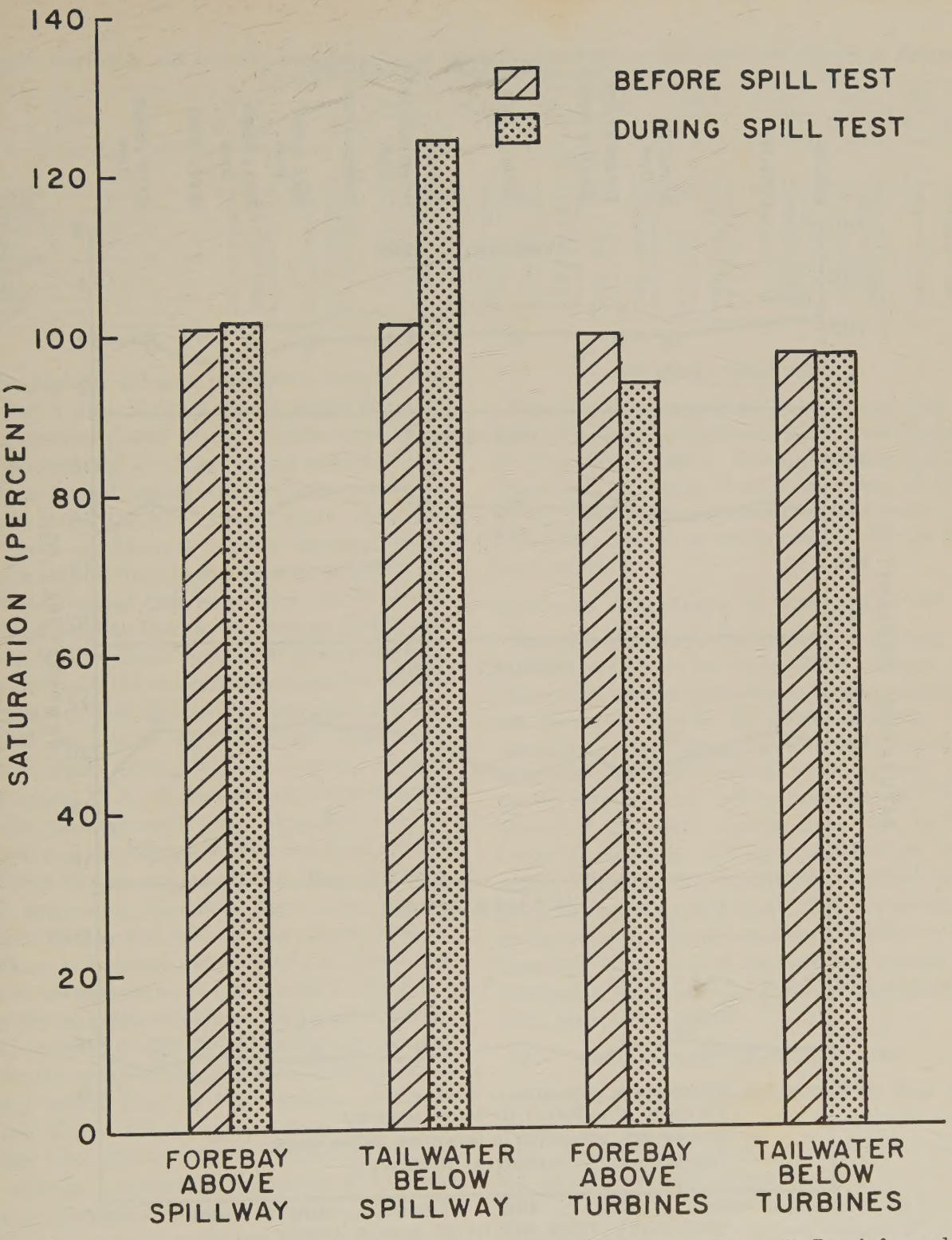

FIGURE 2.—Percentage saturation of dissolved nitrogen in 32 samples taken near Bonneville Dam before and during spill tests, March 3–11, 1966.

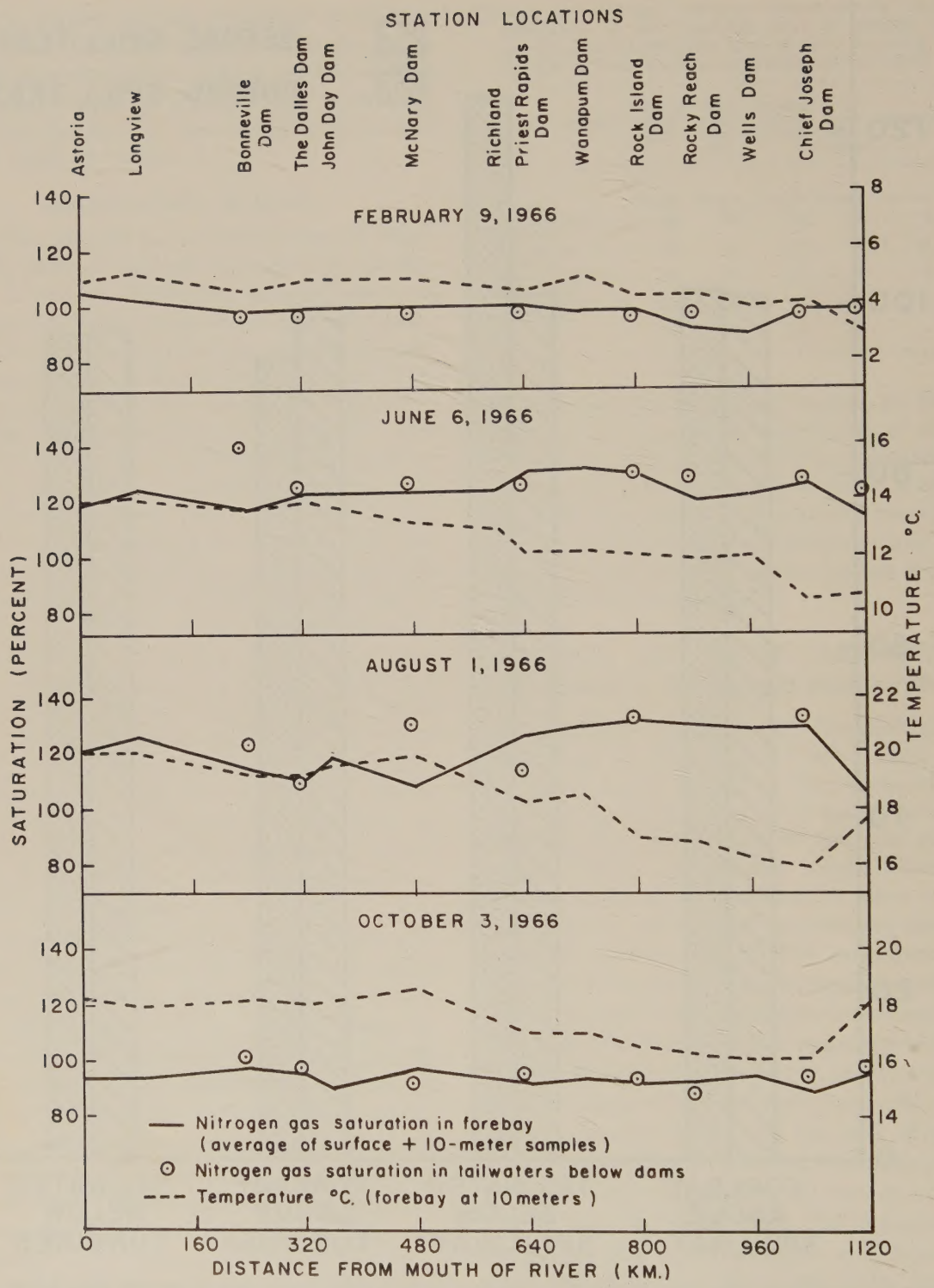

FIGURE 3.—Saturation of dissolved nitrogen and temperature of samples in Columbia River from Astoria to Grand Coulee Dam, February to October 1966.

TABLE 3.—*Mean daily spill (S.) and total flow (T.), in 100 c.m.s. (hundreds of cubic meters per second), at different Columbia River dams, February–November 1966*

Dam	Feb. 9		Mar. 7		Apr. 6		May 9		June 6		July 1		Aug. 1		Sept. 6		Oct. 3		Nov. 7	
	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.
	100 c.m.s.																			
Grand Coulee	0.0	21.8	0.0	21.9	0.0	17.5	19.4	47.2	55.1	74.7	49.7	66.3	22.4	42.9	0.0	19.5	0.0	21.0	0.0	18.4
Chief Joseph	.0	23.2	.0	26.1	.0	15.1	28.8	47.5	60.3	77.9	48.1	71.1	20.7	41.4	.0	22.6	.0	20.6	.0	16.5
Rocky Reach	.0	23.7	.0	22.4	.0	16.5	------	52.0	------	78.1	------	68.5	------	43.6	.0	22.0	.0	20.1	.0	17.5
Rock Island	.0	24.3	.0	23.2	.0	17.4	------	57.7	------	83.5	------	73.3	------	45.4	.0	22.3	.0	20.5	.0	17.5
Wanapum	.0	24.7	.0	27.1	.0	19.4	17.1	54.3	46.0	80.8	31.9	69.2	1.9	44.8	.0	23.1	.0	23.5	.0	22.1
Priest Rapids	.0	25.4	.0	26.9	.0	19.4	21.9	56.2	46.8	81.4	36.3	70.3	36.2	35.7	.0	23.2	.0	23.6	.0	21.5
Ice Harbor	.0	7.1	.0	19.3	.0	19.3	19.3	30.9	9.7	21.0	.0	7.2	.0	6.1	.0	6.2	.0	4.5	.0	6.1
McNary	.0	31.7	.0	26.4	.0	42.8	50.7	91.4	56.7	99.4	41.7	79.1	11.1	54.1	.2	24.6	.0	25.3	.0	25.7
The Dalles	.0	33.0	.0	27.1	.0	46.4	43.4	84.1	60.3	101.0	39.3	80.3	11.5	57.6	.0	26.7	.0	25.3	.0	26.2
Bonneville	.0	33.7	.0	24.3	.0	44.9	59.6	86.5	67.8	99.6	47.3	80.1	23.8	56.6	.0	27.8	.7	26.1	.0	26.6

The highest nitrogen saturation during 1966 occurred in June. Concentrations ranged from 112 to 140 percent; most of the samples were above 120 percent (fig. 3). These values remained high through August between Grand Coulee and Priest Rapids Dams. On July 11 and August 1, however, the river equilibrated rapidly between Priest Rapids and McNary Dams. Concentrations in the forebays dropped from an average of 132 percent at Priest Rapids Dam to an average of 109 percent at McNary Dam. Spilling at Bonneville Dam then increased the saturation to above 120 percent downstream from Bonneville. The rapid equilibration of gas content between Priest Rapids and McNary Dams during July and August was probably caused by the increased circulation of water in the unimpounded river area below Priest Rapids and the lower total flow and spill volumes at Priest Rapids and Ice Harbor Dams (table 3).

In September, Columbia River flows had decreased further and spilling had almost ceased at all dams; this change precipitated a marked reduction in the saturation of nitrogen at all stations—only five samples were above 110 percent. Saturation continued to decrease in October and was well below 110 percent—ranging from 88.4 percent at Rocky Reach Dam to 100.6 percent at Grand Coulee Dam. Water temperatures in October ranged from 16.1° to 18.6° C. (60.8–65.5° F.), and the average temperature was about 1° C. lower than in September. The lack of spilling and lower water temperatures accounted for the decrease in saturation from August to September.

In the last survey during 1966, on November 7, the saturation was not significantly different from that in October 1966 (or November 1965).

DIURNAL VARIATIONS

During a 24-hour period (June 30 and July 1, 1966) of moderately high saturation in the forebay of The Dalles Dam, nitrogen concentrations varied only 0.6 p.p.m. from a maximum of 18.6 p.p.m. (114 percent saturation). Spill volumes at The Dalles Dam were nearly constant for the 24-hour period.

SEASONAL VARIATIONS IN THE SNAKE RIVER

Samples from the tailrace below the spillway of Ice Harbor Dam in the Snake River (station 15) indicated a seasonal variation in amount of nitrogen similar to that in the Columbia River; i.e., normal saturation before spill releases increased saturation as spill releases increased and decreased saturation as spill releases subsided. The timing of the cycle differed from that in the Columbia River, as spilling at Ice Harbor Dam usually began in late April, peaked about mid-May, and ended by mid-June. Thus, the net effect of the Snake River discharge on saturation in the Columbia River was to increase the amount of nitrogen in late April and May and decrease it in June, July, and August.

COMPARISION OF 1966 AND 1967

Saturation of dissolved nitrogen in 1967 followed the same general seasonal changes as in 1966. Values were normal in winter and early spring before the dams began spilling, but rose as spilling increased. Levels again were highest in June and July when the largest volume of water passed through the spillways. When spilling ceased and cooling of the river began in September and October, saturation decreased sharply (fig. 4).

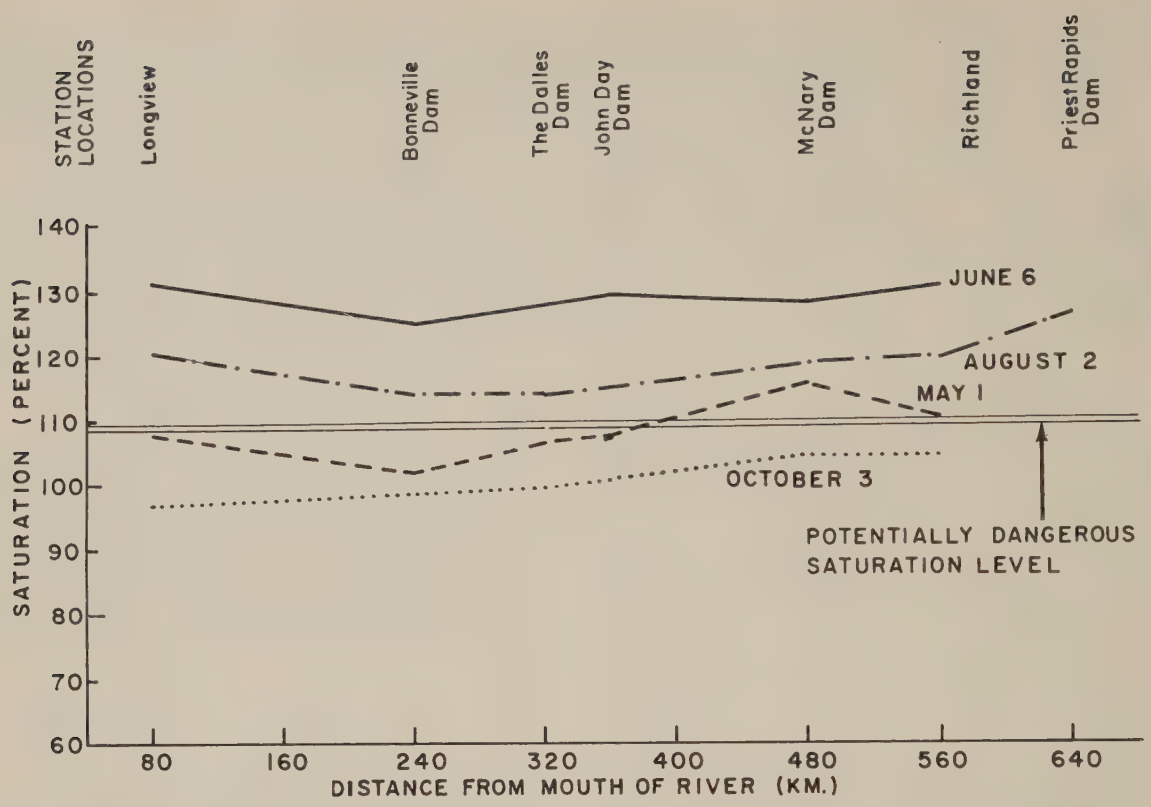

FIGURE 4.—Saturation values of dissolved nitrogen in samples of Columbia River water taken from Longview, Wash., to Priest Rapids Dam, May 1, June 6, August 2, and October 3, 1967. (Values shown are the averages of the surface and 10-m. sample at each location.)

Saturation in May 1967 (102–115 percent) was considerably lower than in May 1966 (110–133 percent) because spillway releases in 1967 were not significant on the main Columbia until late May. By mid-June 1967, however, extremely high spillway releases brought even higher saturations than were recorded in 1966.

In 1966–67 the saturation of dissolved nitrogen over a large area of the river was sufficiently high and of sufficient duration (middle to late May through mid-August) to be a potential danger to migrating juvenile and adult salmon and trout. Experiments by Westgard (1964) showed that adult chinook salmon held in water with concentrations of dissolved nitrogen at 116 percent saturation developed definite symptoms of gas bubble disease. Harvey and Smith (1962) indicated that saturation as low as 108 percent produced gas bubble disease in fingerlings at Cultus Lake Trout Hatchery. These values were much lower than those recorded in the Columbia River. The fish were held in shallow ponds or raceways, however, whereas fish in the Columbia River are usually able to move to greater (compensating) depths, except when they are ascending fishways. The ability of fish to seek compensating depths must be taken into account in the assessment of the effect of high saturation of nitrogen in the Columbia River.

EFFECT OF SUPERSATURATION OF DISSOLVED NITROGEN ON SALMON IN THE COLUMBIA RIVER

Studies of supersaturation of nitrogen in 1967 were made in conjunction with tagging studies designed to determine the cause of loss of adult fish during their migration from Bonneville to Ice Harbor and Priest Rapids Dams.[3] The primary purpose in 1967 was to determine the effect of dissolved nitrogen on juvenile and adult salmon and steelhead known to be in the river when concentrations of dissolved nitrogen were high.

[3] Tagging study in progress by Bureau of Commercial Fisheries, Seattle, Wash.—James H. Johnson, Program Leader.

JUVENILE SALMON

Examination of juvenile chinook salmon that suffered excessive mortality in holding tanks (used for marking fish) at Priest Rapids Dam in 1966 revealed that most fish had symptoms of gas bubble disease. Although the fish otherwise appeared to be sound, they were definitely distressed and, if held, eventually died from gas embolism. Dissolved nitrogen concentrations at Priest Rapids Dam ranged from 114 to 133.9 percent saturation. Temperature in the gatewells of the dam from which fish were collected ranged from 13.9° C. (57° F.) on July 7 to 17.8° C. (64.0° F.) on August 31 when operations ceased. The water temperature in the holding tanks usually rose about 1° to 2° C. before marking began. This slight increase was sufficient to liberate enough gas from the blood of the fish to cause embolism and death. The symptoms of gas bubble disease and distress were eliminated if these fish were held in water slightly cooler than that in the river where they were collected. Usually a decrease of 1° or 2° C. was sufficient to reduce the mortality.

Apparently, juvenile chinook salmon, equilibrated to supersaturation of nitrogen in this temperature range, have considerably less tolerance to increases in temperature than fish that are equilibrated to normal saturation. Brett (1952) in his studies of the tolerance range of juvenile salmon to temperature changes showed that spring chinook salmon acclimated to 10° C. (50° F.) could tolerate temperatures up to 24.5° C. (76.1° F.) before mortalities began. The fish at Priest Rapids Dam, which were acclimated to higher temperatures (13.9–17.8° C.), could not tolerate increases of 1° to 2° C.

It was apparent from observations at Priest Rapids Dam that juvenile migrants were in a precarious situation in July and August. If they did not remain at sufficient depth to compensate for the supersaturation of dissolved nitrogen, they died of gas bubble disease. Their tolerance to temperature increases was also lowered; conceivably sudden temperature increases of only a few degrees centigrade would have caused mortality.

We conducted an experiment in the forebay of Priest Rapids Dam to determine the depth at which juvenile fish must remain to avoid gas bubble disease when subjected to supersaturation of nitrogen. Juvenile coho (*O. kisutch*) and chinook salmon were held in pens submerged at different depths in the forebay and then observed by SCUBA divers at various intervals for symptoms of gas bubble disease. Three tests from 200–280 hours' duration were conducted from May 28 to August 14, 1967, a period when saturation of dissolved nitrogen changed from a high of 143 percent in late May and June to 118 percent in August. Hatchery-reared coho salmon were used in tests 1 and 2 and wild chinook in test 3. One hundred fish were placed in each test cage and in a control cage held in river water of normal saturation at the dam. The first observation was made about 12 hours after placing the cages at the selected depths in the forebay. Other observations were made at 24-hour intervals for the first 4 days; the time between observations was increased thereafter, depending on rate of mortality. Dead fish were brought to the surface by divers and examined for symptoms of gas bubble disease. Neither test nor control fish were fed during the tests. In one test 100 percent of the coho salmon in a surface pen and 70 percent in a pen lowered to a depth of 2 to 3 m. died from gas bubble disease (fig. 5). Three percent was the maximum mortality for control fish held during the test. The experiment showed that at 130 to 140 percent saturation fish must remain below 2.5 m. if they are to be free of symptoms of gas bubble disease. From

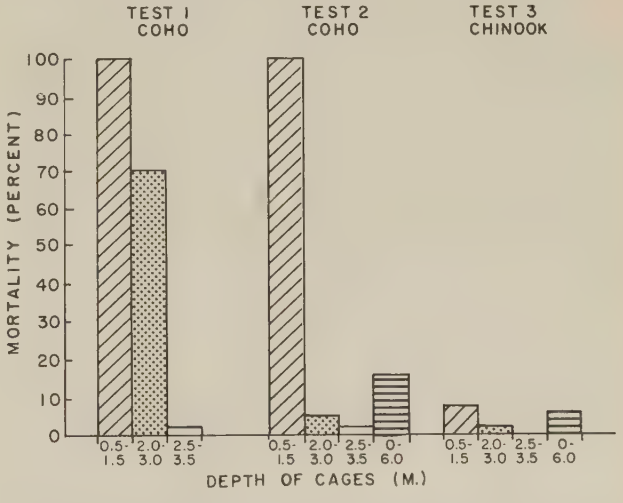

FIGURE 5.—Percentage mortality caused by gas bubble disease during holding experiment in forebay of Priest Rapids Dam May 28 to August 14, 1967. Saturation of dissolved nitrogen ranged from 143 percent in test 1 to 118 percent in test 3; fish were held about 200 hours in tests 1 and 2,280 hours in test 3.

6 to 16 percent of the coho and chinook salmon died in a pen which allowed the fish to seek any depth from the surface to 6 m., which suggested that some mortality may also have occurred to naturally migrating fingerlings even though they could move to any depth.

These field observations of juvenile migrants, though limited, indicate that naturally migrating juvenile fish in the Priest Rapids Dam area are under stress from supersaturation of dissolved nitrogen; it is highly probable that a significant percentage of the fish is lost. The Hanford area of the river downstream from Priest Rapids is of particular concern. Juvenile and adult salmon already under stress must pass areas where thermal reactors emit large volumes of water with temperatures 10° to 15° C. higher than the river temperatures. Obviously, fish under stress from supersaturation of gases have less tolerance to rapid temperature increases, and losses of fish which inadvertently enter the thermal plumes are inevitably high. Further investigation seems imperative on the effect of supersaturation of dissolved nitrogen on the tolerance of salmon to temperature increases.

ADULT SALMON AND STEELHEAD TROUT

About 2,300 adult chinook salmon, 1,600 steelhead trout (*Salmo gairdneri*), and 1,000 sockeye salmon (*Oncorhynchus nerka*) were examined at Bonneville and McNary Dams from mid-April through mid-October 1967 for external symptoms of gas bubble disease. The external symptoms that were used to indicate gas bubble disease were (1) gas bubbles under skin, in roof of mouth, and in fin membranes and (2) hemorrhaging inside the eye and the associated "pop eye" condition of the eyeball. Nitrogen saturation was measured at both dams so that the incidence of disease symptoms could be correlated with the saturation of nitrogen.

Examination of the adult salmon and steelhead trout began on April 11 when saturation was about 106 percent and continued until May 25 when saturation was near 120 percent. Because nitrogen saturation did not exceed 110 percent until May 10, little incidence of gas bubble disease was expected; 1 of 125 steelhead trout examined showed symptoms of the disease (on May 25).

Observations of adult fish at McNary Dam began on June 23 and ended October 11. Nitrogen saturation ranged from 131 percent in June to 104 percent in October. Saturation was high (above 120 percent) from June 23 to July 19 but began to drop sharply after July 19; by August 22, values were below 110 percent. In July, symptoms of gas bubble disease were noted in 10 of 1,000 sockeye salmon, but none were observed in 1,762 chinook salmon and 1,461 steelhead trout. Apparently, chinook salmon and steelhead trout in this area either compensated for the high saturation by remaining at a sufficient depth or the symptoms of the disease had not progressed sufficiently to be evident.

Surveys for carcasses of adult fish were made from April to October during each flight made to obtain water samples. Four additional aerial surveys for carcasses were made during June and July when saturation was highest. Carcasses of eight dead salmon (and a few unidentified fish) were observed; however, it could not be positively verified that any of these fish had died from gas bubble disease. Generally, the fish were too decomposed for determination of cause of death.

Steelhead trout and chinook salmon were observed (June 15 to September 19) congregating in the Columbia River at its confluence with the Snake River. Saturation of dissolved nitrogen in the Columbia ranged from 110 to 130 percent, and temperatures in the Snake River were as much as 5.7° C. (10.3° F.) higher than in the Columbia (table 4). Fish equilibrated to supersaturation of dissolved nitrogen in the Columbia could have died from gas embolism if they had entered the Snake River at this time. A concentrated search on the surface by boat and on the bottom with SCUBA did not yield carcasses of any salmon whose death

TABLE 4.—*Temperature (° C.) and percentage saturation of dissolved nitrogen in the Columbia and Snake Rivers at the mouth of the Snake River—June 6 to Sept. 5, 1967*

Date	Columbia River at mouth of Snake River		Snake River at mouth	
	Temperature	Saturation of dissolved nitrogen	Temperature	Saturation of dissolved nitrogen
	° C.	Percent	° C.	Percent
June 6	13.2	130	12.2	126
June 27	14.2	129	16.3	123
July 5	16.6	129	19.4	113
July 19	17.0	126	22.2	
July 27	18.4	120	23.0	109
Aug. 2	19.1	119	23.7	111
Aug. 9	19.3	118	25.0	108
Aug. 15	21.0	118	24.7	106
Aug. 30	20.3	118	23.5	103
Sept. 5	21.2	110	23.3	105

could be attributed to gas bubble disease or gas embolism. A study of the movement of these fish indicated that many did not reach Ice Harbor Dam.[4] The destination or fate of these fish was not determined.

We have no positive evidence to indicate that the high nitrogen saturation in the Columbia River in 1967 caused serious mortality of adult salmon, but the possibility cannot be discounted. From the surveys and searches made in 1967 it was obvious that it would be difficult to detect a continuous low rate of mortality in a river the size of the Columbia even with continuous surveillance. Various reports of mortality were received from local residents, but again it could not be established that fish had died from gas bubble disease.

SUMMARY AND CONCLUSIONS

A seasonal cycle of supersaturation of dissolved nitrogen occurs each year in the Columbia River. Degree of supersaturation varies with flow of water over spillways of dams. Levels are normal (near 100-percent saturation) in the fall and winter when little or no spilling takes place and high (above 120 percent) in the spring and summer when large volumes of water are being spilled. Water plunging over spillways is the primary cause of supersaturation in the Columbia River.

Water supersaturated with nitrogen does not equilibrate rapidly in reservoirs. Lack of circulation and increases in surface water temperature tend to slow the rate of equilibration. Saturation of dissolved nitrogen in the Columbia River is sufficiently high and occurs over a large area over a sufficiently long time to be potentially dangerous to salmon and steelhead trout. Observations of juvenile salmon at Priest Rapids Dam indicate that supersaturation of nitrogen offers a definite problem; further study is needed to determine its extent.

Field observations to determine the effect of high levels of dissolved nitrogen on adult salmon and steelhead trout were not conclusive. Some sockeye salmon and steelhead trout were observed with symptoms of gas bubble disease, but no chinook salmon had symptoms. A potential problem exists for adult salmon and trout migrating from the Columbia River into the Snake River in July and August. Fish equilibrated to supersaturation of nitrogen from the Columbia River encounter an increase of 5° to 6° C. in temperature on entering the Snake River. The tolerance of the salmon to this temperature change under those conditions is unknown.

[4] Percentage of tag returns from fish subjected to these conditions was about 50 percent lower than returns from other groups passing over Ice Harbor Dam. (Verbal communication, Gerald Monan, BCF Biological Laboratory, Seattle, Wash.)

ACKNOWLEDGMENTS

I thank Richard Westgard of the Washington Department of Fisheries for providing photos of external symptoms of gas bubble disease in adult chinook salmon and for his advice on analytical techniques for dissolved nitrogen. I also thank Richard Krema of the Bureau of Commercial Fisheries, Pasco, Wash., for his help in conducting the holding experiment at Priest Rapids Dam.

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ADDITIONS TO A REVISION OF ARGENTININE FISHES

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ABSTRACT

Four new species of the genus *Argentina* are described, three from the western Atlantic and one from Peru. Range extensions are presented for *A. euchus* from the western Indian Ocean and *A. sialis* from the northeastern Pacific. Speciation in the genus is discussed, and a key is presented to the 12 species recognized. Pigmentation of the swimbladder and its significance as a systematic character are discussed.

A new species of *Glossanodon* from the western Indian Ocean is described, and additional material of *G. polli* from the tropical eastern Atlantic is noted.

Argentinine fishes are taken in commercial quantities in the temperate western North Atlantic (Emery and McCracken, 1966) and are forage fishes in Australia (Fairbridge, 1951). Species found in tropical waters are usually associated with shrimp grounds and are available to shrimp fishing gear. This paper supplements the revision of argentinine fishes published by Cohen in 1958. Since then, additional material has accumulated comprising undescribed species, additional material of poorly known forms, and range extensions. In this paper we reassess the status of populations in the genus *Argentina*. We discuss speciation, comment on swimbladders, and describe one new species from Peru and three from the tropical western Atlantic. Range extensions are recorded for *A. euchus* from the western Indian Ocean and *A. sialis* from the northeastern Pacific. A new species of *Glossanodon* from the western Indian Ocean is described, and additional material of *G. polli* from tropical West Africa is noted.

MATERIALS AND ACKNOWLEDGMENTS

We have received material from the Smithsonian Oceanographic Sorting Center; the U.S. Program in Biology of the International Indian Ocean Expedition; the Guinean Trawling Survey; the Southeastern Pacific Biological and Oceanographic Program; the Bureau of Commercial Fisheries Exploratory Fishing and Gear Research Bases at Pascagoula, Miss., and Seattle, Wash.; and Scripps Institution of Oceanography.

Specimens stored in the following collections have been examined: U.S. National Museum, Wash., D.C. (USNM); Harvard Museum of Comparative Zoology, Cambridge, Mass. (MCZ); Field Museum of Natural History, Chicago, Ill. (FMNH); Stanford University Division of Systematic Biology, Stanford, Calif. (SU); Scripps Institution of Oceanography, La Jolla, Calif. (SIO); British Museum, Natural History, London (BMNH); Museum National d'Histoire Naturelle, Paris (MNHN); Universitetets Zoologiske Museum, Copenhagen (UZMC); University of Miami Marine Laboratory, Miami, Fla. (UMML); Bureau of Commercial Fisheries Tropical Atlantic Biological Laboratory, Miami, Fla. (TABL); Academy of Natural Sciences, Philadelphia, Pa. (ANSP); Tulane University, New Orleans, La. (TU); University of Florida, Gainesville, Fla. (UF); Gulf Coast Research Laboratory, Ocean Springs, Miss. (GCRL); and California Academy of Sciences, San Francisco, Calif. (CAS).

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We thank the curators of the collections listed above for allowing us to examine specimens in their care and providing X-ray photographs. We also thank the many individuals in the field programs listed above who have helped us.

METHODS

Methods and definitions follow Cohen (1958). We note in particular that the split posterior ray of the dorsal and anal fins is counted as two rays and that the vertebral count does not include the urostyle or the hypural fan. The method of counting gill rakers is shown in figure 1. Meristic characters are given as the mode followed by the range in parentheses. Where the range includes data for more than one species, no mode is given. Measurements are given as the mean followed by the range in parentheses.

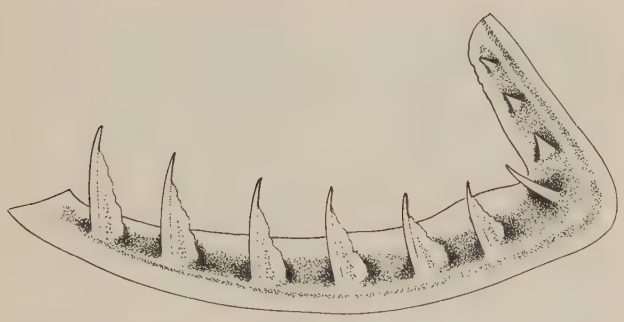

FIGURE 1.—*Argentina striata*, USNM 203001. First gill arch from left side; rakers on lower arm are counted as six. Gill filaments are not shown. Drawn by Mildred H. Carrington.

GENUS *ARGENTINA* LINNAEUS

For this genus, we divide the species into two groups and discuss sympatry and its significance, taxonomic significance of the swimbladder, and present a key to the species of *Argentina*.

SPECIES GROUPS

The 12 species of *Argentina* are divided into two groups.

Species Group 1

Four species are in this group. They are *silus* and *sphyraena* from the North Atlantic and Mediterranean and *sialis* and *aliceae* from the eastern Pacific. This group is distinguished by its larger jaw, almost always greater than 21.5 percent of head length (fig. 2), and usually more gill rakers (7–21 on the lower arm of the first gill arch; one species, *A. sphyraena*, has few gill rakers, 7–10, but the other three species have 11–21; see table 1). The species in this group are allopatric (although the gross geographical ranges of *sphyraena* and *silus* overlap, they are ecologically separate, mainly living and certainly spawning at different depths), and are very distinct morphologically.

Species Group 2

Eight species are in this group. They are *striata*, *brucei*, *georgei*, and *stewarti*, all from the western Atlantic; *euchus*, from the western Indian Ocean; and *elongata*, *australiae*, and *kagoshimae* from the western Pacific. This group is distinguished by its shorter jaw, almost always less than 20 percent of head length, and generally fewer gill rakers (5–10, but one species, *A. elongata*, has more gill rakers, 8–10; the other species have 5–8). At least some of the species in this group are sympatric.

SYMPATRY AND ITS SIGNIFICANCE

Cohen (1958) treated the forms (then three, a fourth is described in this paper) constituting the *silus* group as full species. However, the three western Pacific forms of the *striata* group, *australiae*, *elongata*, and *kagoshimae*, were recognized as subspecies because these disjunct populations (Australia, New Zealand, and Japan, respectively) are very similar to each other, far more so than are the species in the *silus* group (see key). *A. striata* was recognized as a full species, but could just as easily have been ranked as a subspecies. *A. euchus* (Cohen, 1961) was given full species rank because it was described from only two specimens.

Subsequent study of hundreds of specimens from the western Atlantic has shown that what was formerly considered to be a single species, *A. striata*, clearly comprises four forms. These forms are similar to each other and separated by few characters. In fact, they are distinguished, one from the other, by characters which both qualitatively and quantitatively resemble those that separate the western Pacific forms.

We recognize the four closely related western Atlantic forms as full species because at least some of them are sympatric. *A striata* and *brucei* have been taken together in trawl hauls off Venezuela (*Atlantis* sta. 2700; *Oregon* sta. 1989, 4410, and 4465). *A. brucei* and *stewarti* were taken together off Nicaragua (*Oregon* sta. 3574 and 3610). *A.*

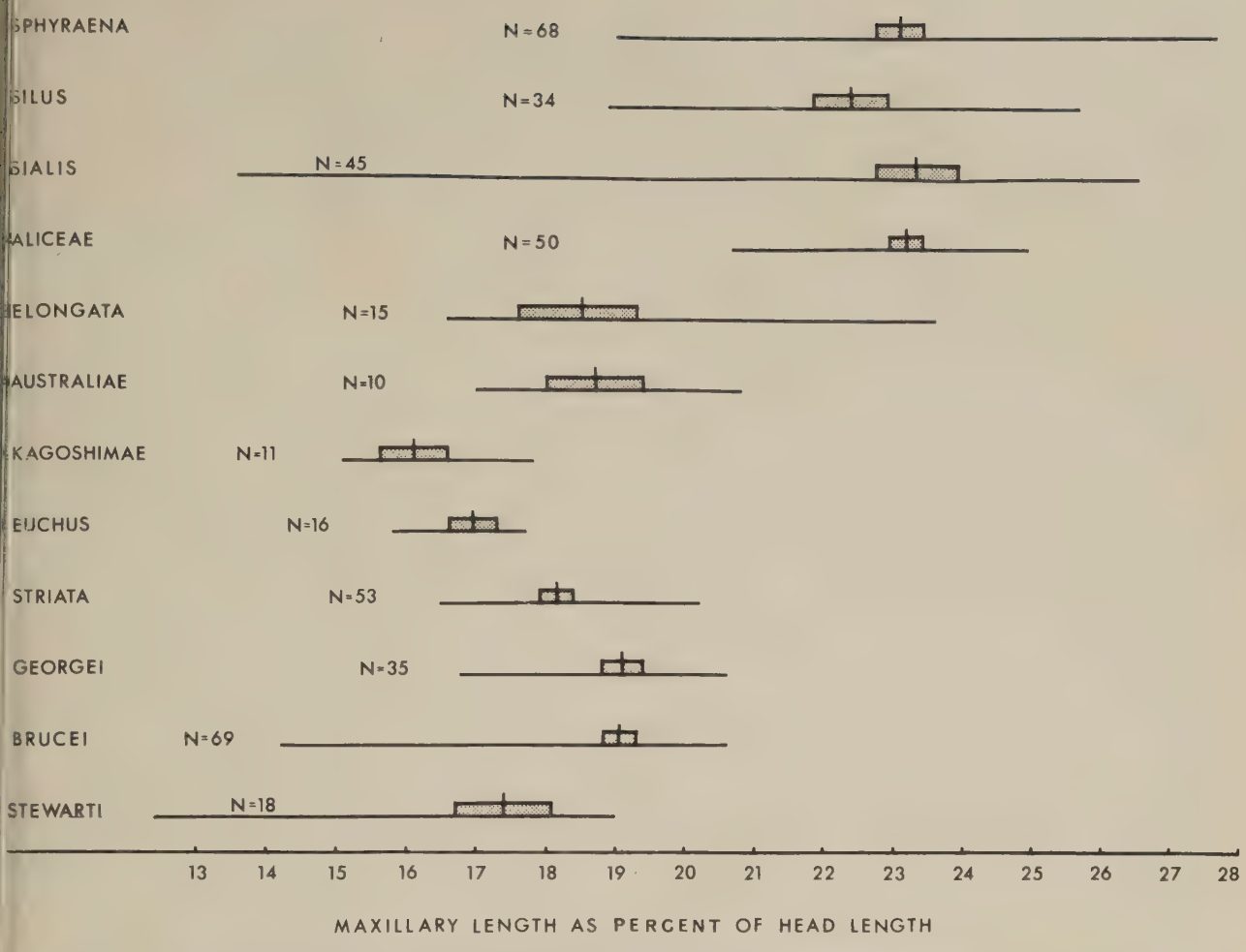

FIGURE 2.—Two species groups of *Argentina* as shown by maxillary length as percent of head length. Horizontal lines are ranges; bars are two standard errors on each side of means; vertical lines are means.

georgei and *brucei* have been taken together off Honduras (*Oregon* 3626) and at closely adjacent localities at similar depths off the south coast of Jamaica (*Oregon* 3549 and 3548). *A. georgei* and *stewarti* were caught in the same trawl off the Virgin Islands (*Oregon* sta. 2606). *A. striata* and *georgei* were caught at approximate localities and depths off the east coast of Florida, south of Dry Tortugas, and on the north coast of Cuba.

Figure 3 shows the distribution and figure 4 summarizes the co-occurrence of the four species. *A. brucei* and *georgei* each live with three other western Atlantic species; *striata* and *stewarti* each with two others. Only *A. striata* and *stewarti* are not so far known to co-occur.

We treat the four tropical western Atlantic forms as full species because they are sympatric, even though the magnitude of differences between them is less than the magnitude of differences separating species of the *silus* group. Although the western Pacific forms are not known to be sympatric, we recognize them also as full species. It is obvious that in the genus *Argentina*, characters of the magnitude of those separating *elongata*, *australiae*, and *kagoshimae* can signal the existence of full species.

SWIMBLADDER

The occurrence of silvery pigment in the outer layers of the swimbladded of some species of *Argentina* has been noted many times in the literature. Cohen (1958) added the observation that some species of *Argentina* lack this silvery pigment. He commented that presence or absence of silvery pigment did not seem to be a function of age, size, time of year, or method of preservation,

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FIGURE 3.—Distribution of four species of *Argentina* in the western Atlantic.

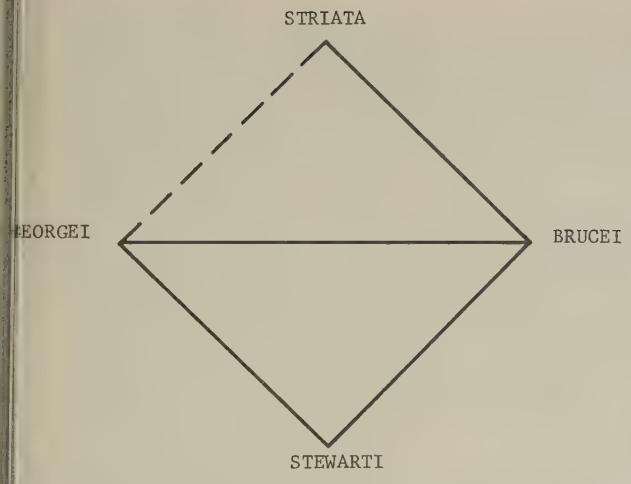


FIGURE 4.—Co-occurrence of four species of *Argentina* in the western Atlantic. Solid lines connect species taken from the same trawl. A dotted line connects species taken in different trawls at the same or closely adjacent localities.

and he, therefore, used the character taxonomically, although always in company with other characters. We here point out errors in Cohen's observations and comment on the variability of this character. In his key to the species of *Argentina* and in his diagnosis of *A. striata* Cohen stated that *A. striata* lacked a silvery-pigmented swimbladder. We have examined the swimbladders of 150 specimens of *A. striata* from throughout the range of the species and find that most, though not all of them, have definite silvery pigment. Cohen probably based his 1958 statement on examples of one or more of the other three species of *Argentina* from the western Atlantic.

The swimbladder of *A. striata* may have any one of four patterns of pigmentation. In one, the entire outer part of the organ is heavily coated with guanine (fig. 5); in the second, the anterior and posterior quarters of the bladders are pigmented with guanine, but the intervening segment lacks silvery pigment (fig. 5); in the third, only the posterior segment is pigmented with guanine; in the fourth and rarest type, the outer layer is faintly iridescent or appears to lack any impregnation of guanine.

In all but two instances, all specimens of *A. brucei* lack silvery pigment on the swimbladder (fig. 5). In a collection of six specimens from Venezuela (UF 5237), five individuals have iridescent to silvery pigment on each swimbladder, and a single individual lacks pigment completely. Also, one of three specimens from Honduras (FMNH 74571) has a silvery swimbladder.

All specimens examined of *A. stewarti* lack definite silvery pigment (fig. 5); however, one had a slightly iridescent swimbladder. A few examples of *A. georgei* have slightly iridescent swimbladders.

The specimens of *A. australiae*, *elongata*, and *kagoshimae* listed by Cohen (1958) were reexamined. The bladders were iridescent in *australiae;* pigment was lacking in the other two species.

The swimbladder pigmentation patterns discussed in this paper are valid only in preserved specimens.

Fänge (1958) has suggested that guanine might help to keep gases in the bladder. It would be interesting to test the diffusion rate of gases through the swimbladder walls of pigmented and unpigmented species of *Argentina.* In this respect we note that the small posterior chamber of the *Argentina* swimbladder, first described by Cohen (1958) and shown by Fahlén (1965) to have a resorbent function, invariably lacks silvery pigment.

According to Cohen (1958), argentinine fishes are physoclists that lack a rete mirabile. Such a condition is, of course, highly improbable unless there is some unknown method of gas being secreted into and maintained in the swimbladder. *Argentina* does in fact have a rete, which has been described for *A. silus* by Fänge (1958). He noted that it is a unique structure, different from the rete of other kinds of fishes. Marshall (1960) named it a micro-rete and described it in several other genera of argentinoid fishes.

KEY TO SPECIES OF *ARGENTINA*

1a. Branchiostegal rays 6, scales with spines ..... *2.*
1b. Branchiostegal rays 5, scales lacking spines ..... *3.*
2a. Lateral line scales 52 (50–54); gill rakers on lower arm of first arch 8 (7–10) .... *A. sphyraena.*
2b. Lateral line scales 67 (64–69); gill rakers on lower arm of first arch 13 (11–17) .. *A. silus.*
3a. Gill rakers on lower arm of first arch 14–21; jaw relatively large, snout to maxillary tip distance usually less than 5 in head ..... *4.*

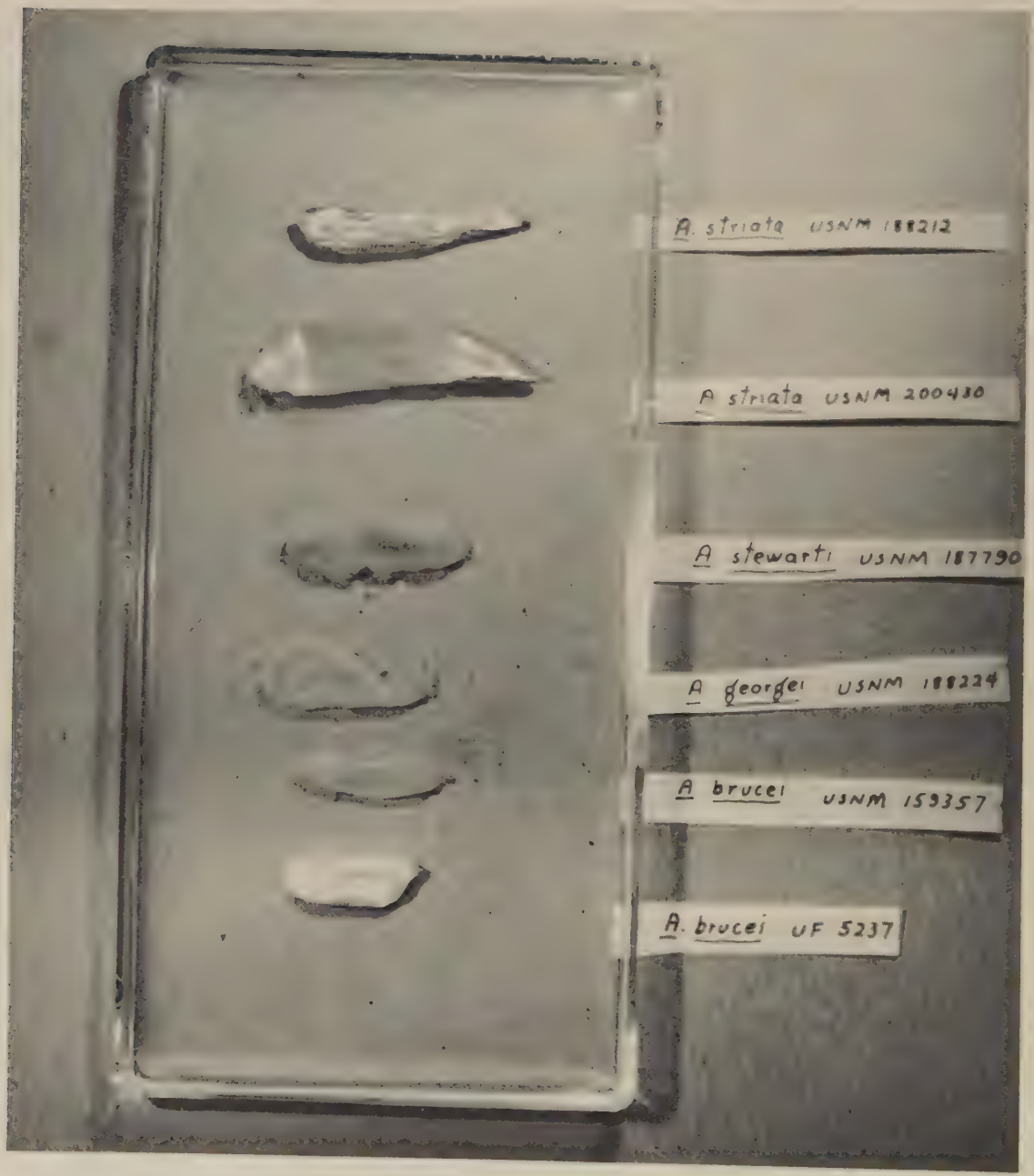

A. striata USNM 188212
A striata USNM 200430
A stewarti USNM 187790
A georgei USNM 188224
A brucei USNM 159357
A. brucei UF 5237

FIGURE 5.—Swimbladders from four species of western Atlantic *Argentina*. See text for explanation.

3b. Gill rakers on lower arm of first arch 5–10; jaw relatively small, snout to maxillary tip distance usually more than 5 in head ..... 5.
4a. Head 3.0 (2.7–3.1) in standard length; eye 11.5 (10.5–12.7) in standard length; vertebrae 44 (43–45); lateral line scales 47 (45–48) ..... *A. aliceae* p. 19.
4b. Head 3.5 (3.2–3.7) in standard length; eye 14.3 (12.7–16.4) in standard length; vertebrae 48 (47–50); lateral line scales 49 (48–51) ..... *A. sialis* p. 22.
5a. Gill rakers on lower arm of first arch 9 (8–10) ..... *A. elongata.*
5b. Gill rakers on lower arm of first arch 5–7 ..... 6.
6a. Pectoral fin rays 13–14 ..... *A. australiae.*

6b. Pectoral fin rays 15 or more ..... 7.
7a. Ventral fin rays 10–12 ..... 8.
7b. Ventral fin rays 12–15, usually 13 or more ..... 9.
8a. Lateral line scale rows 54 (51–54); ventral fin rays 11–12, usually 12; anal fin rays 11–13, usually 12 or fewer; vertebrae 50–51 ..... *A. kagoshimae.*
8b. Lateral line scale rows 49 (47–50); ventral fin rays 10–11, usually 10; anal fin rays 13 or more; vertebrae 47–48 ..... *A. euchus* p. 33.
9a. Gill rakers on lower arm of first arch usually 7; vertebrae 45 (44–46) ..... *A. brucei* p. 31.
9b. Gill rakers on lower arm of first arch usually 6; vertebrae 47–54 ..... *10.*
10a. Swimbladder usually with definite silvery pigment or iridescence; pectoral fin rays 19 (18–21); body depth in standard length 8.2 (6.4–10.3); caudal peduncle depth in head length 5.2 (4.4–6.0); vertebrae 49 (47–51) ..... *A. striata* p. 22.
10b. Swimbladder lacking silvery pigment, sometimes iridescent; pectoral fin rays 17 (16–19); body depth in standard length 9.5 (7.4–12.0); caudal peduncle depth in head length 6.4 (5.6–7.3); vertebrae 48 (47–50) ..... *A. georgei* p. 27.
10c. Swimbladder lacking silvery pigment, sometimes iridescent; pectoral fin rays 20 (19–21); body depth in standard length 11.8 (9.1–13.6); caudal peduncle length in head length 6.0 (5.5–7.1); vertebrae 52–53 ..... *A. stewarti* p. 29.

ARGENTINA ALICEAE, NEW SPECIES

Figures 2, 6

Diagnosis

This species can be separated from *A. sphyraena* and *silus* by its smooth instead of spiny scales and by its five instead of six branchiostegals. *A. aliceae* differs from *sialis* in having a longer head, 33.7 (32.3–36.7) percent of standard length, in *sialis* 28.8 (27.3–31.2); a larger eye, 8.7 (7.9–9.5), in *sialis* 7.0 (6.1–7.9); fewer vertebrae, 44 (43–45), in *sialis* 48 (47–50); and fewer lateral line scales, 47 (45–48), in *sialis* 49 (48–51). It differs from all other species of *Argentina* in having 16 to 21 gill rakers on the lower arm of the first arch rather than 5 to 10.

Counts

See tables 1 to 7.

Measurements

Based on about 100 specimens, 83.2 to 143 mm. standard length, given as percent of standard length. Predorsal 48.6 (46.0–50.6); head length 33.7 (32.3–36.7); snout 10.5 (9.7–11.6); eye 8.7 (7.9–9.5); maxillary length 7.8 (7.0–9.1); depth at dorsal fin 17.3 (15.1–20.0); depth caudal peduncle 7.5 (6.9–8.7).

Description

Greatest depth at dorsal origin, tapering to caudal peduncle. Body in cross section deeper than wide; belly rounded. The head, when viewed laterally, has its dorsal profile slightly broken by the margin of the eye; the ventral profile rises to

FIGURE 6.—*Argentina aliceae*, USNM 202462, holotype, 147 mm. standard length. All scales not shown. Cross section from in front of dorsal fin. Drawn by Mildred H. Carrington.

TABLE 1.—*Gill rakers on lower arm of first arch in species of* Argentina

Species	Gill rakers																
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	Number of fish																
sphyraena			2	27	17	4											
silus							3	13	23	10	1						
sialis										1	2	9	22	6	4	1	
aliceae												1	8	29	13	3	1
elongata				5	13	12											
australiae		9	1														
kagoshimae	2	14															
euchus		17															
striata		76	2														
georgei		41	1														
brucei		1	87														
stewarti		21	1														

TABLE 2.—*Vertebral counts in species of* Argentina

Species	Number of vertebrae																
	43	44	45	46	47	48	49	50	51	52	53	54	—	64	65	66	67
	Number of fish																
sphyraena			1		1	3	1			1	5	4					
silus														2	2	2	1
sialis					4	67	13	1									
aliceae	1	47	27														
elongata									1	6	10	1					
australiae							2	2	3	1							
kagoshimae								2	5								
euchus					11	5											
striata					3	22	111	13	2								
georgei					4	31	8	4									
brucei		12	101	6													
stewarti										17	5						

TABLE 3.—*Dorsal fin ray counts in species of* Argentina

Species	Dorsal fin rays								
	9	10	11	12	13	14	15	16	17
	Number of fish								
sphyraena		12	46	3					
silus			2	32	23				
sialis			5	35	8				
aliceae			11	85	5				
elongata		3	12	4					
australiae		5	6	1					
kagoshimae		4	10	2					
euchus				15					
striata		1	39	18					
georgei		1	38	1					
brucei		1	67	5					
stewarti		1	14	6					

TABLE 4.—*Anal fin ray counts in species of* Argentina

Species	Anal fin rays								
	9	10	11	12	13	14	15	16	17
	Number of fish								
sphyraena			1	12	33	23	1		
silus					1	4	32	12	3
sialis					9	26	6		
aliceae					23	33	3		
elongata			4	5	7	4			
australiae				3	8				
kagoshimae			6	6	1				
euchus					9	5	1		
striata			3	20	34				
georgei		12	20	8	2				
brucei			9	36	27				
stewarti				11	10				

TABLE 5.—*Pectoral fin ray counts in species of* Argentina

Species	Pectoral fin rays										
	11	12	13	14	15	16	17	18	19	20	21
	Number of fish										
sphyraena		5	24	42	2						
silus					5	13	28	11			
sialis	5	35	8								
aliceae						1	20	14			
elongata			1	9	9	1					
australiae			8	3							
kagoshimae					6	9	2				
euchus						5	10	1			
striata								3	26	24	2
georgei						1	23	13	4		
brucei								30	30	4	
stewarti								1	7	8	6

TABLE 6.—*Ventral fin ray counts in species of* Argentina

Species	Ventral fin rays					
	10	11	12	13	14	15
	Number of fish					
sphyraena	6	49	6			
silus			44	13		
sialis	3	40	5			
aliceae	4	84	7			
elongata		13	6			
australiae		6	5	13		
kagoshimae		3	14			
euchus	14	2				
striata			4	9	40	3
georgei			4	22	8	
brucei				43	21	
stewarti				9	9	3

ABLE 7.—*Lateral line scales in three species of* Argentina

Species	Lateral line scales						
	45	46	47	48	49	50	51
	Number of fish						
lis				7	20	18	1
ceae	1	21	58	16			
chus			1	4	11	1	

he snout in a gentle curve; the interorbital space etween the supraocular canals is broadly concave. he frontals laterad to the canals arch upward ightly. The dorsal portion of the maxillary is idden under the lacrimal and the jugal bones. The istal end of the maxillary is closer to the anterior argin of the eye than to the snout. Some speci- ens have a slight, bony knob at the symphysis of he lower jaw. The jaws are subequal; the upper roadly rounded, the lower less so. The palatine nd the head of the vomer bear a continuous band to 4 teeth wide composed of small, closely spaced, onical teeth; about 50 on the vomer and 25 to 30 n each palatine; dentary teeth are lacking. The eratobranchial of the fifth gill arch bears 7 to 10 mall, conical teeth; two patches of similar teeth, to 10 on the anterior patch and 10 to 15 on the osterior patch, are found at the anterior end of he fourth suprabranchial. The tongue bears 6 trong recurved teeth (description of dentition ased on a single alizarin-stained specimen). The ill rakers are elongate, compressed, and relatively idely spaced; the longest gill rakers are equal o about one-third of the interorbital distance.

The pectoral fin originates slightly ahead of a ertical through the posterior tip of the opercle. The anterior end of the pectoral fin base is elevated from the horizontal by an angle of 30 to 45 degrees. The distance between the bases of the innermost rays of the pectoral fins is less than the least depth of the caudal peduncle. The greatest height of the dorsal fin is usually greater than the maximum depth of the body. The greatest height of the anal fin is greater than the least depth of the caudal peduncle. The pectoral fins extend more than one-half the distance between the bases of the pectoral and ventral fins; the ventral fins are slightly shorter.

The scales lack spines. The lateral line scale count is summarized in table 7.

The peritoneum is colored with large, dark chromatophores, which are most densely distributed in the antero-dorsal section of the body cavity; the gut is immaculate. Ten to 14 pyloric caeca are present in 12 specimens. The body cavities of all specimens examined contained considerable amounts of fat.

The elongate swimbladder extends from about the level of the curve of the stomach to about the midlength of the ventral fin. The anterior tip of the swimbladder bears some silvery pigment, and the posterior one-third to one-half of the organ is strongly impregnated with silvery pigment.

Pigmentation in alcohol of adult specimens is light straw-colored on the lower two-thirds of the fish; the dorsum is darker; the muzzle is dusky, as are the nape and the upper portion of the opercle. Many specimens have the remnants of an iridescent band along the midline. In fishes less than about 95 mm. standard length, there is a series of 8 to 10 dusky blotches along the upper third of the body. In life the fish is a bright silvery color (H. A. Fehlmann, Smithsonian Oceanographic Sorting Center, personal communication).

Teratology

A single specimen from *Anton Bruun* sta. 640–B (USNM 202472) lacks pectoral fins. An X-ray photograph shows that a pectoral girdle is present.

Distribution

A. aliceae is known from nine localities along the northern coast of Peru, where it has been trawled at depths of 50 to 54 fm. (91–99 m.) to 105 to 170 fm. (192–311 m.); most specimens were taken between 55 and 88 fm. (100–161 m.).

Habits

This species has been taken only in bottom trawls and like most other *Argentina* apparently travels in schools a short distance above the bottom. The largest catch recorded was from *Anton Bruun* sta. 641–A, where 1,440 individuals weighing 44 kg. were taken. Several specimens examined had their stomachs tightly packed with partially digested crustaceans. Annotated station data from *Anton Bruun* cruise 16, which collected most of the study material, are presented by Chin (1966).

Name

Named for Alice Holland, former Secretary of this Laboratory, in recognition of her devoted services to ichthyology.

Study Material

All study material from Peru. Holotype: USNM 202462, 147 mm. standard length; R.V. *Anton Bruun* cruise 16, station 641–A, 6°54′ S., 80°44′ W., 97 to 110 m.; 6 June 1966; otter trawl. Paratypes: USNM 202459 (84 specimens, 1 cleared and stained); data as for holotype; from the same station MCZ (5); SIO (5). Paratypes: USNM 202460 (97); *Bruun* 640–B, 7°01′ S., 80°44′ W., 105 m.; otter trawl; from the same station USNM 202472 (1 lacking pectoral fins); FMNH (5); CAS (3). USNM 202463 (18); *Bruun* 639–A, 6°47′ S., 80°43′ W., 100 to 91 m.; otter trawl. USNM 202465 (1); *Bruun* 635–A, 6°27′ S., 80°56′ W., 160 m.; otter trawl. USNM 202464 (3); *Bruun* 631–A, 5°59′ S., 81°12′ W., 100 m.; otter trawl. USNM 202461 (320), *Bruun* 630–A, 6°02′ S., 81°12′ W., 160 m.; otter trawl; from the same station BMNH (5); UZMC (4); MNHN (3); ANSP (3). USNM 202466 (4); *Bruun* 627–A, 5°02′ S., 81°24′ W., 192 to 311 m.; otter trawl. USNM 202467 (2); *Bruun* 625–A, 4°57′ S., 81°23′ W., 118 to 133 m.; otter trawl. USNM 199802 (4); SW. of Lobos de Afuera Islands, Peru, 110 m.; trawl.

ARGENTINA SIALIS GILBERT

Figure 2

The heretofore northernmost locality for *A. sialis* is Monterey Bay, Calif. (Follett, 1945). An extension of the known range of about 1,120 km. is provided by a single specimen (147 mm. standard length) taken by the *John N. Cobb* off the coast of Oregon on 3 March 1962: USNM 188126, 46°04′ N., 124°39′ W., 100 to 102 fm. (183–187 m.), otter trawl, bottom temperature 8.3° C. The specimen agrees well with the description given by Cohen (1958).

Additional vertebral counts based on specimens from southern California listed by Cohen (1958) are presented in table 2.

ARGENTINA STRIATA GOODE AND BEAN

Figures 1, 2, 3, 4, 5, 7, 8, 9, 10A

Argentina striata Goode and Bean, 1896, p. 52, pl. 17, fig. 62 (original description; type-locality *Albatross* station 2402, 28°36′ N. 85°33′ W., Gulf of Mexico, 111 fm. Holotype: USNM 43858, not designated in text of original description, but on p. 4 of the Atlas in the caption for pl. 17, fig. 62).

Diagnosis

This species can be separated from *A. sphyraena* and *silus* by its smooth instead of spiny scales and by its five instead of six branchiostegals. It differs from *silus*, *sialis*, *aliceae*, and *elongata* in having 6 (occasionally 7) gill rakers on the lower arm of the first arch, whereas the four species listed above have 8 to 21. It also differs in gill raker count from *A. brucei*, which has 7 (occasionally 6) rakers; also *striata* has 47 to 51 vertebrae; *brucei* has 44 to 46. It differs from *euchus* in having 12 to 15 ventral rays rather than 10 or 11. It differs from *kagoshimae*, *australiae*, *elongata*, *sialis*, and *sphyraena* in having 18 to 21 rather than 11 to 17 pectoral rays. It differs from *georgei* and *stewarti* in usually having silvery pigment on the swimbladder, whereas the others lack it; from *stewarti* in having 47 to 51 vertebrae rather than 52 or 53; from *georgei* in having caudal peduncle depth in head length usually less than 5.7 rather than usually more than 5.7.

Counts

See tables 1 to 6.

Measurements

Based on about 55 specimens, 88.0 to 173 mm. standard length, given as percent of standard

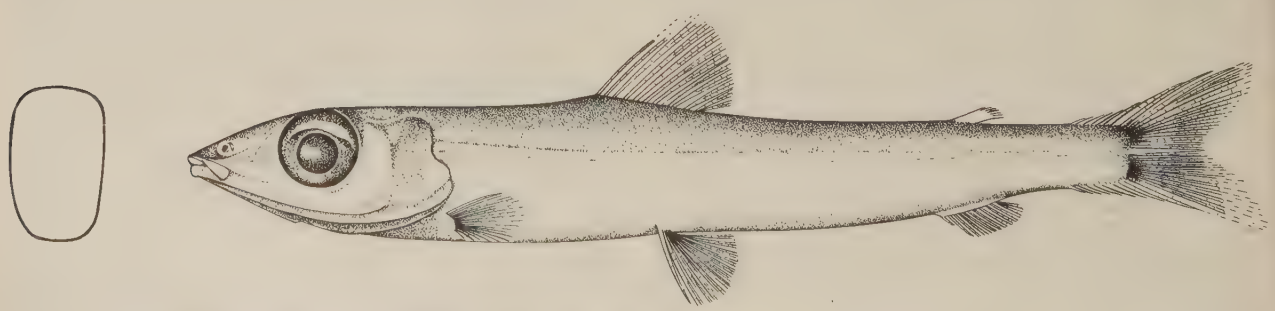


FIGURE 7.—*Argentina striata*, USNM 203003, 154 mm. standard length. Cross section from in front of dorsal fin. Scales not drawn. Drawn by Mildred H. Carrington.

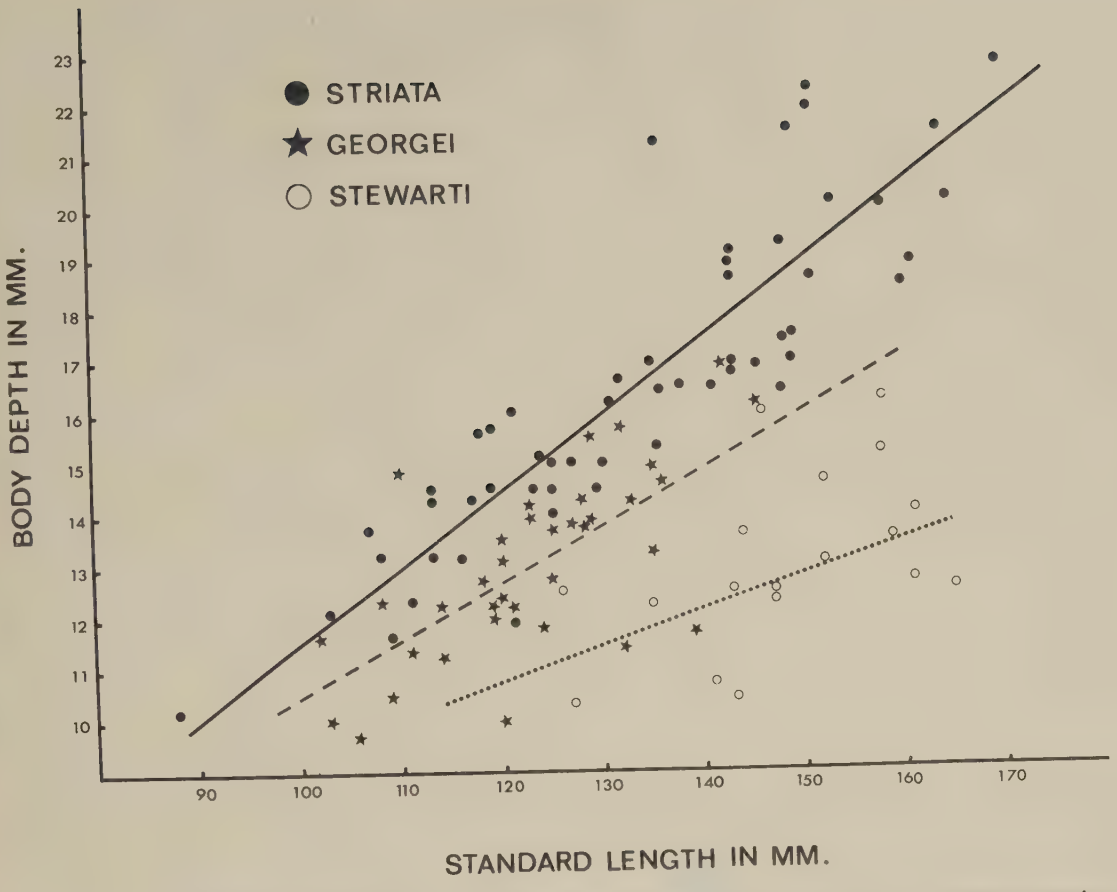


FIGURE 8.—Regressions of body depth (mm.) on standard length (mm.) for three closely related species of *Argentina*. See text for equations.

length. Preanal 83.5 (80.8–85.9); preventral 55.5 (52.2–58.0); predorsal 46.6 (44.2–48.6); head length 30.1 (26.1–32.0); snout 9.6 (8.5–10.6); eye 9.8 (7.8–10.9); maxillary length 5.4 (4.2–6.1); depth at dorsal fin 12.3 (9.7–15.7); depth caudal peduncle 5.8 (5.2–6.5).

Description

Body not very elongate. Greatest depth at dorsal origin, tapering to caudal peduncle. Figure 8 shows a regression of body depth on standard length ($Y=.150X-3.50$) compared with two closely related species. The caudal peduncle is also relatively deep. Figure 9 shows a regression of caudal peduncle depth on head length ($Y=.180X+.524$) compared with two closely related species. Body in cross section deeper than wide, dorsum and venter broadly rounded. The head, when viewed laterally, has its dorsal profile barely if at all broken by the upper margin of the eye; the ventral profile rises to the snout in a gentle curve; many specimens are preserved with the mouth open and the basibranchial projecting into the ventral profile. The interorbital space between the supraocular canals is flat or only slightly concave. The dorsal portion of the maxillary lies under the lachrymal. The distal end of the maxillary is usually about midway between the tip of the snout and the anterior margin of the eye. The jaws are broadly rounded, the lower slightly included. The palatine and the head of the vomer bear small, closely spaced, needlelike teeth in a continuous band from 2 to 5 teeth wide, about 30 on the vomer and 40 on each palatine; dentary teeth are lacking. The ceratobranchial of the fifth gill arch bears 9 small, conical teeth; two patches of similar teeth, 10 on the anterior patch and 14 on the posterior patch are at the anterior end of the fourth suprabranchial; there are also a few teeth on the third suprabranchial. The tongue bears eight strong recurved teeth (description of dentition based on a

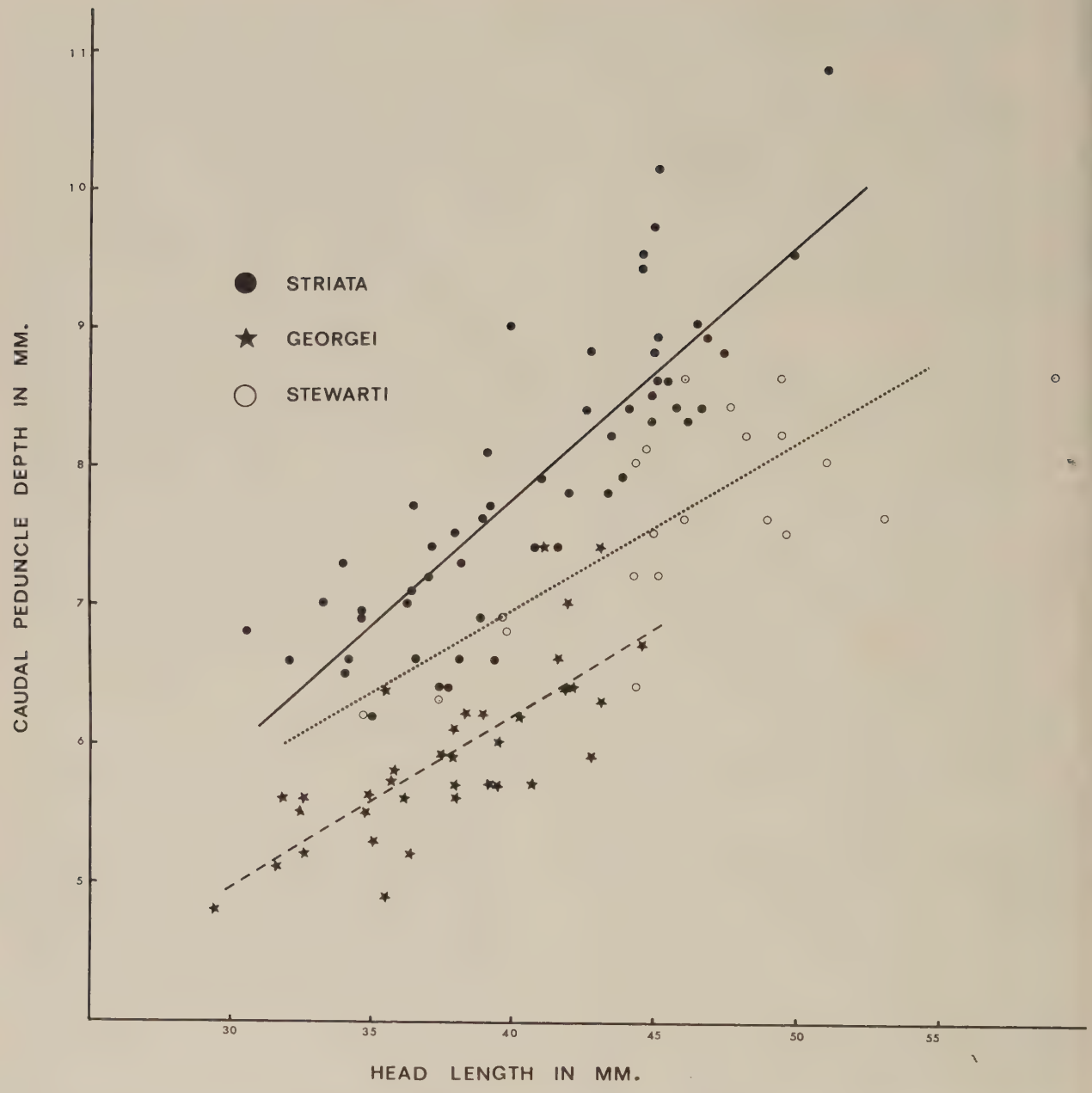


FIGURE 9.—Regressions of caudal peduncle depth (mm.) on head length (mm.) for three closely related species of *Argentina*. See text for equations.

single alizarin specimen). The gill rakers (fig. 1) are medium-sized, compressed, and widely spaced. The longest gill rakers are equal to one-fifth to one-sixth of the interorbital distance.

The pectoral fin originates close to the posterior margin of the opercle. The anterior end of the pectoral fin base is elevated from the horizontal by an angle of about 45 degrees; the distance between the innermost rays of the pectoral fins is about equal to or slightly less than the least depth of the caudal peduncle. In almost all of our specimens the pectoral and ventral fins are broken off short; however, in a few specimens, the pectorals appear to extend at least half the distance from the pectoral base to the ventral base. The ventral fins are probably shorter.

Scales and scale pockets are deciduous; however, ıe few scales we have seen lack spines. Lateral ne counts of scale pockets in several specimens :e about 50.

The peritoneum is black or almost so ventrally, rading to a less dense distribution of chro-atophores laterally, then a darker band along ıe kidneys. The gut is immaculate. Nine to 14 yloric caeca are present in 12 specimens. Most pecimens have considerable fat in the body cavity. The swimbladder begins slightly anterior to the ind curve of the stomach and extends posteriorly) about the tip of the ventral fin. In 137 swim-ladders examined, only 6 lacked any silvery pig-ıent and several of these were iridescent. About ne-half of the specimens having swimbladders ıat were completely impregnated with silvery uanine also had silvery pigment on the head, sug-esting that strong formaldehyde solution that issolves the silvery pigment on the body may also issolve away pigment from the middle part of he swimbladder.

Pigmentation of adult specimens preserved in ormaldehyde solution is variable, but in general he ventral two-thirds of the body is light. There s often a brown band above the lateral line; in ome examples the band is barely discernible (fig. '), in others quite distinct. Although the dark pig-ıent of the peritoneum may show through the hin belly musculature, there is no externally pig-ıented band along the midventral line. Some pecimens have the throat peppered with brown hromatophores (fig. 10A); in many, however, his region is immaculate. Specimens less than bout 100 mm. standard length may have a row f eight or nine dusky blotches along the upper hird of the body, but not all do. Alcohol-pre-erved specimens are silvery below the lateral line nd on most of the head.

Distribution

A. striata is widely distributed in the western Atlantic, ranging from the offing of Nova Scotia (Schroeder, 1955), along the east coast of the United States, the north coast of Cuba, around the Gulf of Mexico, in the northwestern and southern Caribbean, and off the mouths of the Orinoco. There are two records, however, from much farther south off Brazil. Carvalho (1950) described specimens from Banco Sao Tomé at about lat. 22° S., and Miranda Ribeiro (1961) described and figured specimens from 24°14′ S., 44°49′ W. We have not examined material from either locality, but the descriptions fit our material of *A. striata.*

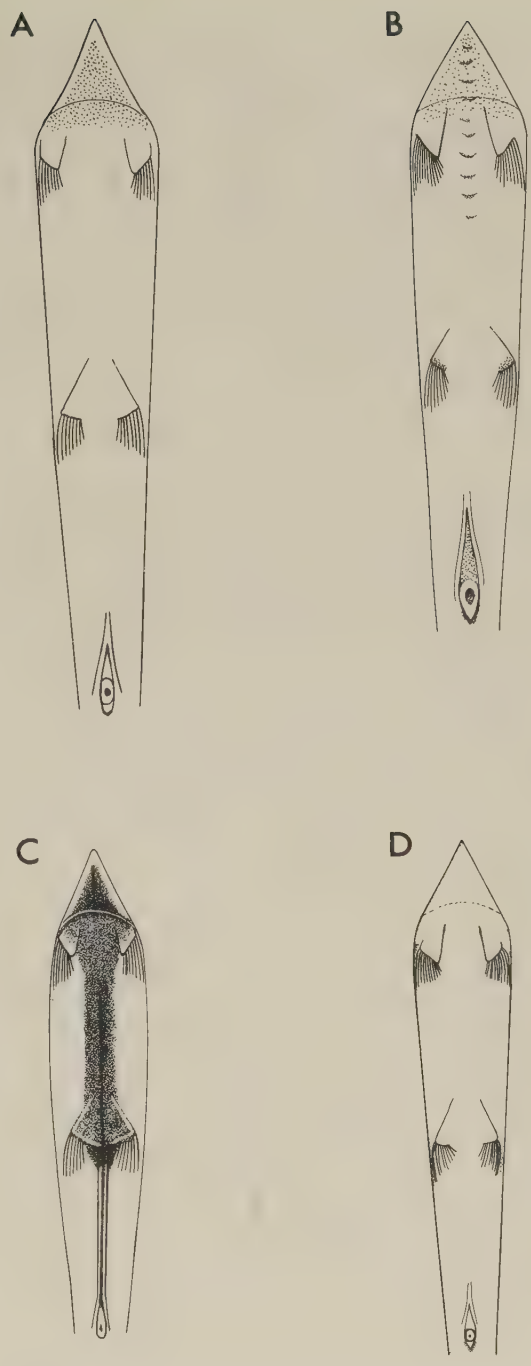


FIGURE 10.—Pigmentation on venters of four western Atlantic species of *Argentina:* A. *striata,* USNM 203001; B. *stewarti,* USNM 187834; C. *georgei,* USNM 186356; D. *brucei,* USNM 187793. Drawn by Mildred H. Carrington.

In the West Indies, *A. striata* has been taken only off the northern coast of Cuba and around the southern end of the Lesser Antilles; the records of *striata* given by Cohen (1958, 1964), Springer and Bullis (1956), and Bullis and Thompson (1965) from Hispaniola and the Lesser Antilles are of *striata*, *stewarti*, *georgei*, or *brucei*, or of combinations of these four.

Depth distribution ranges from 80 to 260 fm. (146–476 m.), but most records are from between 100 and 240 fm. (183–439 m.).

Habits

A. striata is taken with a bottom trawl, usually over a mud bottom at bottom temperatures ranging from 48° to 59° F. (8.9–15° C.). Specimens are caught singly and also in aggregations of as many as 100 individuals. Mixed collections of *A. striata* and *A. brucei* have been taken in the same haul.

Study Material

All from the Atlantic.

Bahama Banks.—MCZ 38476 (1 specimen), 22°45′ N., 78°45′ W., 150 to 180 fm. (274–329 m.). MCZ 40614 (1), 22°46′ N., 78°45′ W., 195 to 225 fm. (357–412 m.). UMML 11689 (10), 27°08′ N., 79°53′ W., 110 fm. (201 m.).

U.S. Atlantic.—UMML 12127 (21), 27°10′ N., 79°55′ W., 100 fm. (183 m.). MCZ 39817 (2), 27°17′ N., 79°49′ W., 200 fm. (366 m.). USNM 158082 (1), *Pelican* 25, 28°03′ N., 79°52′ W., 150 to 175 fm. (274–320 m.). TU 14774 (1), *Pelican* 60, 28° 29′ N., 79°54′ W., 160 to 190 fm. (293–348 m.). TABL 100559 (1), *Combat* 319, 28°31′ N., 79°52′ W., 180 fm. (329 m.). USNM 156659 (1), *Pelican* 204–4, 28°59′ N., 80°01.5′ W., 100 fm. (183 m.). USNM 188905 (1), *Oregon* 5094, 29°31′ N., 80°09′ W., 210 fm. (384 m.). TABL 100564 (11); *Silver Bay* 217, 29°41′ N., 80°08′ W., 180 to 200 fm. (329–366 m.). SU 49755 (1), 29°47′ N., 80°12′ W. TABL 100558 (1), *Silver Bay* 212, 29°59′ N., 80°07′ W., 200 fm. (366 m.). UMML 1461 (2) and UMML 529 (1), NE. coast of Florida, ESE. St. John's River Entrance, 105 fm. (192 m.). MCZ 38305 (4), 37°00′ N., 74°00′ W., 150 fm. (274 m.). MCZ 34568 (1), 37°36′ N., 74°17′ W., 100 fm. (183 m.). MCZ 38213 (9), 37°38′ N., 74°15′ W., 120 to 130 fm. (220–238 m.). USNM 186300 (1), *Delaware* 15–B, 37°42′ N., 74°12′ W., 150 to 225 fm. (274–412 m.). MCZ 39778 (6), 38°36′ N., 73°10′ W. MCZ 38341 (1), 38°38′ N., 73°10′ W., 190 to 200 fm. (348–366 m.). MCZ 37947 (1), 39°58′ N., 69°28′ W., 105 to 140 fm. (192–256 m.). MCZ 39973 (1), 39°59′ N., 69°35′ W , 82 to 85 fm. (150–155 m.). MCZ 37419 (1), *Captain Bill II* 35, 40°02′ N., 70°24′ W., 105 to 110 fm. (192–201 m.).

U.S. Gulf of Mexico.—UMML 16905 (1); 24°18′ N. 82°52′ W., 190 fm. (348 m.). UMML 16651 (1); 24°19′ N., 82°29′ W., 103 fm. (188 m.). TU 10901 (5); *Oregon* 1005, 24°20′ N., 83°20′ W., 190 fm. (348 m.). TU 12695 (12); *Oregon* 1548, 24°25′ N., 83°00′ W., 210 fm. (384 m.). TU 10917 (4); *Oregon* 1007, 24°26′ N., 83°24′ W., 180 fm. (329 m.). FMNH 66231 (1); *Oregon* 2671, 24°26′ N., 83°24′ W., 212 fm. (388 m.). FMNH 66230 (10); *Oregon* 2670, 24°27′ N., 83°26′ W., 210 fm. (384 m.). UMML 13289 (5); *Oregon* 4362, 24°30′ N., 83°33′ W., 190 fm. (348 m.). SU 49753 (1); *Oregon* 1009, 24°34′ N., 83°34′ W., 200 fm. (366 m.). SU 49726 (1); FMNH 59880 (19); *Oregon* 1026, 25°08′ N., 84°19′ W., 163 fm. (298 m.). TU 12669 (9); *Oregon* 1556, 26°24′ N., 98°45′ W., 210 fm. (384 m.). UMML 4441 (1); 28°07′ N., 85°13′ W., 150 fm. (274 m.). USNM 158687 (1); *Oregon* 953, 28°23′ N., 85°51′ W., 180 fm. (329 m.). SU 49724 (1); *Oregon* 1276, 28°30′ N., 86°11′ W., 240 fm. (439 m.). USNM 158686 (2); GCRL V60:119 (6); *Oregon* 36, 28°30′ N., 85°36′ W., 120 fm. (220 m.). USNM 43858, *holotype* and USNM 83864, *paratype* (1); *Albatross* 2402, 28°36′ N., 85°33′ W., 111 fm. (203 m.). FMNH 46270 (12); *Oregon* 277, 28°48′ N., 85°40′ W., 104 fm. (190 m.). TU 11698 (2); *Oregon* 1520–30, 29°00′ N., 88°00′ W., 200 to 250 fm. (366–457 m.). GCRL V62:731 (1); *Oregon* 3697, 29°00′ N., 88°36.5′ W., 190 to 200 fm. (348–366). USNM 203086 (1); *Oregon* 3725, 29°00.5′ N., 88°35.5′ W., 220 fm. (402 m.). USNM 156658 (2); *Pelican* 9, 29°02′ N., 88°41.5′ W., 120 to 169 1/2 fm. (220–310 m.). USNM 203087 (1); *Oregon* 3763, 29°03′ N., 88°34′ W., 190 fm. (348 m.). USNM 159349 (7); *Silver Bay* 156, 29°04′ N., 85°49′ W., 100 to 102 fm. (183–187 m.). USNM 188212 (18), TABL 100557 (2) and USNM 187836 (3); *Oregon* 3646, 29°07′ N., 88°34′ W., 125 fm. (229 m.). SU 49725 (1); *Oregon* 273, 29°09′ N., 85°59′ W., 110 fm. (201 m.). GCRL V63:933 (1); *Oregon* 60, 29°09′ N., 88°33′ W., 110 fm. (201 m.). GCRL V63: 932 (2); *Oregon* 32, 29°10′ N., 85°55′ W., 95 fm. (174 m.). USNM 188387 (1); GCRL V62: 730 (1); *Oregon* 3676,

29°10′ N., 88°10′ W., 200 fm. (366 m.). UMML 508 (1); 29°10′ N., 88°20′ W., 150 fm. (274 m.). USNM 188389 (3); *Oregon* 3677, 29°11′ N., 88°06′ W., 200 fm. (366 m.). USNM 158127 (1); SU 49727 (1); *Oregon* 1246, 29°15′ N., 88°11′ W., 200 to 210 fm. (366–384 m.). SU 17441 (1); 29°15.5′ N., 87°53′ W. FMNH 45932 (2); *Oregon* 864, 29°19′ N., 86°04′ W., 82 fm. (150 m.). FMNH 46269 (5); *Oregon* 265, 29°20′ N., 87°42′ W., 101 fm. (185 m.). USNM 159013 (1); *Oregon* 1260, 29°23′ N., 86°48′ W., 250 fm. (457 m.). SU 49723 (1) and FMNH 46268 (2); *Oregon* 269, 29°27.5′ N., 87°26.5′ W., 150 fm. (274 m.). USNM 158842 (1); *Oregon* 1400, 29°30′ N., 87°08′ W., 210 fm. (384 m.). TU 11761 (2); *Oregon* 946, 29°41′ N., 86°44′ W., 100 fm. (183 m.). TU 2716 (7); *Oregon* 278, 29°49′ N., 85°45′ W., 112 fm. (205 m.).

Mexico.—SU 49721 (1); *Oregon* 1054, 19°37′ N., 92°40′ W., 200 fm. (366 m.). FMNH 45728 (1); *Oregon* 726, 22°41.9′ N., 86°41.2′ W., 225 fm. (412 m.). USNM 186068 (2); *Silver Bay* 1184, 23°56′ N., 87°32′ W., 150 fm. (274 m.). TU 12939 (7); UF 1316 (2); *Oregon* 1091, 26°46′ N., 96°20′ W., 200 to 210 fm. (366–384 m.). FMNH 46266 (2); *Oregon* 550, 26°55′ N., 96°25.5′ W., 125 fm. (229 m.). TU 10998 (4); *Oregon* 1094, 27°10′N., 96°20′ W., 150 fm. (274 m.). FMNH 45050 (1); 27°15′ N., 96°15′ W., 200 fm. (366 m.). TU 2770 (4); *Oregon* 1164, 27°21′ N., 96°06′ W., 160 fm. (293 m.). USNM 203000 (1); *Oregon* 4617, 27°48′ N., 94°37′ W., 200 fm. (366 m.).

Central America.—USNM 187835 (1); *Oregon* 3634, 16°44′ N., 87°55′ W., 190 fm. (348 m.).

South America.—UF 8026 (2); FMNH 66223 (11); *Oregon* 1989, 9°45′ N., 59°45′ W. USNM 203046 (1); *Oregon* 4465, 10°45′ N., 66°37′ W., 125 fm. (229 m.). USNM 203003 (5); *Albatross* 2700, 10°59′ N., 66°00′ W., 140 fm. (256 m.). TABL 100556 (4); *Oregon* 5037, 11°36′ N., 62°46′ W., 200 to 240 fm. (366–439 m.). USNM 203002 (1); *Oregon* 4410, 11°52′ N., 69°27′ W., 230 fm. (421 m.). USNM 200430 (1); *Oregon* 5690, 12°30′ N., 72°08′ W., 257 fm. (470 m.).

Antilles.—MCZ 40617 (1); *Albatross* 3422, 22°48′ N., 79°09′ W., 235 fm. (430 m.). MCZ 40010 (1); 22°49′ N., 79°07′ W., 235 fm. (430 m.). MCZ 40618 (1); 22°52′ N., 79°22′ W., 240 fm. (439 m.).

ARGENTINA GEORGEI, NEW SPECIES

Figures 2, 3, 4, 5, 8, 9, 10C, 11

Diagnosis

This species can be separated from *A. sphyraena* and *silus* by its smooth instead of spiny scales and by its five rather than six branchiostegals. It differs from *silus*, *sialis*, *aliceae*, and *elongata* in having 6 (occasionally 7) gill rakers on the lower arm of the first arch—the four species listed above have 8 to 21. It differs in gill raker count from *A. brucei*, which has 7 (occasionally 6) rakers; also *georgei* has 47 to 50 vertebrae, *brucei* has 44 to 46. It differs from *euchus* in having 12 to 14 ventral rays rather than 10 or 11. It differs from *sphyraena*, *sialis*, *elongata*, and *australiae* in having 16 to 19 pectoral rays rather than 11 to 16. It differs from *kagoshimae* in having vertebrae usually less than 50 rather than usually more than 50; pectoral rays 16 to 19 rather than usually less than 17; ventral rays usually 13 or 14 rather than 11 or 12. It differs from *striata* in lacking silvery pigment on the swimbladder; in having anal rays usually 10 or 11 rather than 12 or 13, pectoral rays usually 17 or 18 rather than 19 or 20, and caudal peduncle depth in head length usually more than 6 rather than 6 or less. It differs from *stewarti* in having 47 to 50 vertebrae rather than 52 or 53, in

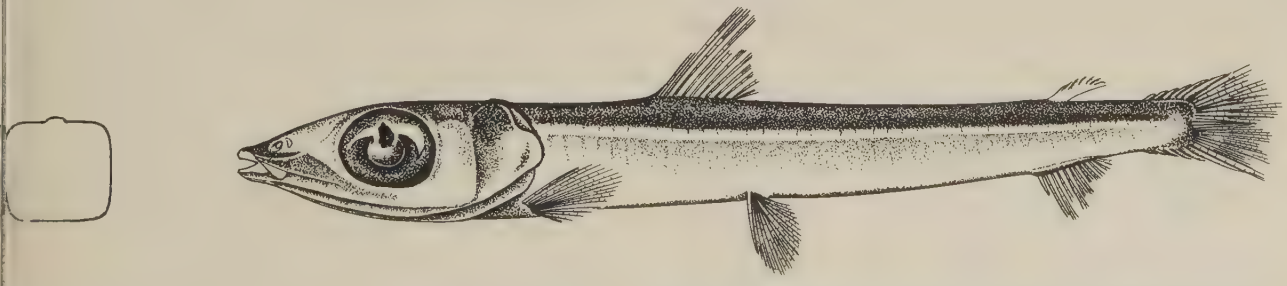


FIGURE 11.—*Argentina georgei*, USNM 188224, paratype, 109 mm. standard length. Scales not shown. Cross section from in front of dorsal fin. Drawn by Mildred H. Carrington.

having usually 10 or 11 anal rays rather than 12 or 13, and in having pectoral rays usually 17 or 18 rather than 19 to 21.

Counts

See tables 1 to 6.

Measurements

Based on 37 specimens, 102 to 146 mm. standard length given as percent of standard length. Preanal 85.1 (83.3–86.3); preventral 55.6 (53.7–58.6); predorsal 46.4 (44.9–48.6); head length 30.6 (28.5–32.4); snout 10.0 (8.7–11.2); eye 9.4 (8.2–10.9); maxillary length 5.8 (5.2–6.6); depth at dorsal fin 10.6 (8.3–13.4); depth caudal peduncle 4.8 (4.3–5.6).

Description

Body of medium length. Figure 8 shows a regression of body depth on standard length ($Y=.120X-.504$) compared with two closely related species. Greatest depth behind head, tapering to the relatively narrow caudal peduncle. Figure 9 shows a regression of caudal peduncle depth on head length ($Y=.123X+1.28$) compared with two closely related species. Body in front of dorsal fin almost square in cross section or somewhat wider than deep; compressed posteriorly. Dorsum and venter flat, not rounded. The head, when viewed laterally, as deep or deeper than the body, its dorsal profile barely or not at all broken by the upper margin of the eye; the dorsal and ventral profiles of the head converge at about equal angles on the snout. The interorbital space between the supraocular canals is broadly concave. The dorsal portion of the maxillary lies under the lachrymal. The distal end of the maxillary reaches to at least the midpoint of the distance from the tip of the snout to the anterior margin of the orbit and usually farther. The jaws are broadly rounded, the lower included; there is a slight, bony protuberance behind the symphysis of the lower jaw. The palatine and the head of the vomer bear small, closely spaced, needlelike teeth in a continuous band 2 to 5 teeth wide, about 40 on the vomer and 50 on each palatine; no dentary teeth. The ceratobranchial of the fifth gill arch bears 8 small, conical teeth; two patches of similar teeth, 5 on the anterior patch and 15 on the posterior patch, are at the anterior end of the fourth suprabranchial. The third suprabranchial lacks teeth. The tongue bears eight strong, recurved teeth (description of dentition based on a single alizarin-stained specimen). The gill rakers are medium-sized, compressed, and widely spaced. The longest rakers equal one-seventh to one-eighth of the interorbital distance.

The pectoral fin originates on the ventral surface of the fish anterior to a vertical through the rear margin of the opercle; the distance between the innermost rays of the pectoral fins is equal to or, more often, greater than the least depth of the caudal peduncle. The fin rays of all specimens are broken off short.

Scales deciduous, the few we have seen lack spines. Lateral counts of scale pockets in several specimens are about 50.

The peritoneum is dark. The gut is immaculate. Eight or nine pyloric caeca are present in eight specimens. The swimbladder begins close to the hind curve of the stomach and extends posteriorly to slightly beyond the origin of the ventral fin. Swimbladder lacking silvery pigment (fig. 5), however, we have seen several specimens with slightly iridescent bladders.

Pigmentation of adult specimens preserved in formaldehyde is distinctive and consists of a dark brown band extending along the upper quarter of the side; it is not continuous over the dorsum; however, there is a dark, middorsal streak. The venter and throat of most specimens are pigmented with large, dark chromatophores which form a wide dark band extending to the pelvics (fig. 10C), and in many specimens all the way to the vent. In some specimens the superficial pigmentation of the belly is poorly developed, and in these the darkly pigmented peritoneum shows through the thin ventral musculature.

Distribution

A. georgei is found off the east coast of Florida and barely enters the Gulf of Mexico south of Dry Tortugas. It has also been taken at several localities along the western side of the Bahama Banks and on the north coast of Cuba. In the Caribbean and along the Antilles, *A. georgei* has been trawled off Honduras, Nicaragua, and Jamaica and near Puerto Rico and the Virgin Islands (fig. 4).

Depth distribution ranges from 120 to 250 fm. (220–457 m.), but the fish has been most often caught between 150 and 220 fm. (274–402 m.).

Habits

A. georgei has been taken only in bottom trawls over mud and shell bottoms at bottom tempera-

ures of 48, 58, 61, and 62° F. (8.9, 14.4, 16.1, and 6.7° C.). Specimens are most often taken singly. ur largest sample has six individuals. *A. georgei* as been taken with *brucei* and with *stewarti*.

ame

Named for George Clipper, to whom we are in-ebted for efficient assistance in this Laboratory.

tudy Material

All from the Atlantic. Holotype: USNM 203016, 25 mm. standard length, *Oregon* 3622, 16°01′ N., 1°08′ W., 145 to 150 fm. (265–274 m.), June 6, 962. Paratypes:

Bahama Banks.—FMNH 65791 (1 specimen), *regon* 1343, 22°59′ N., 79°17′ W., 250 fm. 457 m.). TABL 100575 (1), *Silver Bay* 2457, 3°43′ N., 79°07′ W., 250 fm. (457 m.). FMNH 3217, *Combat* 446, 25°10′ N., 79°13′ W., 250 fm. 457 m.). UF 1350 (1), *Combat* 235, 27°27′ N., 8°58′ W., 180 fm. (329 m.). USNM 158689 (1), *Combat* 237, 27°28′ N., 78°44′ W., 215 fm. (393 m.).

U.S. Atlantic.—TABL 100563 (4), *Combat* 441, 5°16′ N., 80°00′ W., 185 fm. (338 m.). TABL 00569 (1), *Silver Bay* 2482, 26°07′ N., 79°12′ W., 00 fm. (366 m.). TABL 100567 (1), *Silver Bay* 18, 29°38′ N., 80°11′ W., 220 fm. (402 m.). ABL 100573 (5), *Combat* 491, 29°30′ N., 80°10′ V., 125 fm. (229 m.).

U.S. Gulf of Mexico.—UMML 2882 and 2545 1 each); *Combat* 281, 24°17′ N., 82°47′ W., 215 fm. 393 m.).

Central America.—USNM 187841 (5), *Oregon* 579, 12°26′ N., 82°26′ W., 125 fm. (229 m.). USNM 203017 (4) and MCZ (2), *Oregon* 6423, 3°28′ N., 82°01′ W., 150 to 158 fm. (274–289 m.). USNM 187839 (6), *Oregon* 3566, 14°10′ N., 1°58′ W., 150 to 160 fm. (274–293 m.). USNM 88224 (4), *Oregon* 3622, data as for holotype. USNM 187834 (3, 1 cleared and stained), *Oregon* 625, 16°26′ N., 81°35′ W., 120 fm. (220 m.). ANSP 98604 (4), *Oregon* 3626, 16°45′ N., 81°27′ W., 150 fm. (274 m.).

Antilles.—USNM 187816 (2); *Oregon* 3548, 17°53′ N., 77°56′ W., 150 fm. (274 m.). TABL 100572 (3); *Silver Bay* 5193, 18°16′ N., 67°22′ W., 150 fm. (274 m.). FMNH 66224 (1); *Oregon* 2606, 18°37.5′ N., 65°04′ W., 210 fm. (384 m.). USNM 157980 (1); *Oregon* 1344, 22°50′ N., 79°08′ W., 200 to 225 fm. (366–412 m.). USNM 157976 (1); *Oregon* 1343, 22°59′ N., 79°17′ W., 250 fm. (457 m.).

ARGENTINA STEWARTI, NEW SPECIES

Figures 2, 3, 4, 5, 8, 9, 10B, 12

Diagnosis

This species can be separated from *A. sphyraena* and *silus* by its smooth instead of spiny scales and by its five instead of six branchiostegal rays. It differs from *silus*, *sialis*, *aliceae*, and *elongata* in having 6 (occasionally 7) gill rakers on the lower arm of the first arch—the four species listed above have 8 to 21. It differs in gill raker count from *A. brucei* which has 7 (occasionally 6) rakers. *A. stewarti* differs from *sialis*, *aliceae*, *kagoshimae*, *euchus*, *striata*, *georgei*, and *brucei* in having 52 or 53 vertebrae—the others have 43 to 51. It differs from *sphyraena*, *sialis*, *elongata*, *australiae*, and *kagoshimae* in having 18 to 21 pectoral rays rather than 11 to 17. It differs from *sphyraena*, *sialis*, *aliceae*, *elongata*, *kagoshimae*, and *euchus* in having 13 to 15 ventral rays rather than 10 to 12. It differs from *striata* in lacking silvery pigment on the swimbladder (occasionally lacking in *striata*) and in its more slender body, depth usually 10 or more times in standard length rather than usually less than 9 in standard length in *striata*. It differs from *georgei* in having anal rays 12 or 13 rather than usually 10 or 11 and in having pectoral rays usually 19 or more, rather than usually 18 or fewer.

Counts

See tables 1 to 6.

FIGURE 12.—*Argentina stewarti*, USNM 202998, paratype, 148 mm. standard length. Scales not shown. Cross section from in front of dorsal fin. Drawn by Mildred H. Carrington.

Measurements

Based on 18 specimens, 121 to 166 mm. standard length, given as percent of standard length. Preanal 85.0 (83.5–86.7); preventral 55.8 (53.8–57.3); predorsal 47.7 (46.4–49.1); head length 30.6 (28.8–33.0); snout 10.3 (10.1–10.5); eye 9.7 (8.7–10.7); maxillary length 5.3 (3.8–5.9); depth at dorsal fin 8.6 (7.3–11.0); depth caudal peduncle 5.1 (4.5–5.5).

Description

Body elongate. Figure 8 shows a regression of body depth on standard length ($Y=.069X+2.43$) compared with two closely related species. Greatest depth behind head, tapering little to the caudal peduncle. Figure 9 shows a regression of caudal peduncle depth on head length ($Y=.112X+2.44$) compared with two closely related species. Body in cross section in front of dorsal fin usually wider than deep, approximately rectangular. The head, when viewed laterally, has its dorsal profile slightly interrupted by the upper margin of the eye; the ventral profile of the head rises gently to the snout. The interorbital space between the supraocular canals flat or barely concave. The dorsal portion of the maxillary lies under the lachrymal. The distal end of the maxillary is midway between the tip of the snout and the anterior margin of the orbit. The jaws are broadly rounded, the lower included. The palatine and the head of the vomer bear small, closely spaced, needlelike teeth in a continuous band 2 to 5 teeth wide, about 30 on the vomer and 45 on each palatine; no dentary teeth. The ceratobranchial of the fifth gill arch bears 14 small, conical teeth; two patches of similar teeth, with about 18 on each are found at the anterior end of the fourth suprabranchial. The tongue bears eight strong recurved teeth (description of dentition based on a single alizarin specimen). The gill rakers are widely spaced triangular flaps; the longest ones are equal to one-seventh to one-eighth of the interorbital distance.

The pectoral fin originates on the ventral surface of the body anterior to a line through the hind margin of the opercle. The distance between the inner rays of the pectoral fins is equal to or greater than the least depth of the caudal peduncle. The rays of all fins are broken off short.

Scales deciduous; the few we have seen lack spines. Lateral scale pockets about 55.

The peritoneum is densely punctulate with small dark chromatophores. Several specimens have the gut lightly peppered with chromatophores. Seven to nine pyloric caeca are present in eight specimens. The swimbladder begins close to the hind curve of the stomach and extends posteriorly to beyond the origin of the ventral fin. Swimbladder lacking silvery pigment (fig. 5); however, we have seen one specimen with an iridescent swimbladder.

Pigmentation of adult specimens preserved in formaldehyde solution consists of a dark brown band extending along the upper one-fourth of the body; ventral and parallel to the band is a less darkly pigmented area. These two pigment bands color the entire upper one-half of the body. The dorsum is unpigmented with the exception of a narrow middorsal streak. The throat and breast are peppered with chromatophores, which in some specimens are also scattered at the bases of the ventral fins (fig. 10B). In some specimens the peritoneum shows through the belly as a dark, midventral streak. Some specimens also have some of the scale pockets of the venter outlined in dark pigment.

Distribution

A. stewarti has been taken off Nicaragua in the western Caribbean and from Mona Island to Dominica in the Antilles (fig. 4). It seems likely that it is widespread in the southern Caribbean.

Depth distribution ranges from 200 to 310 fm. (366–567 m.)—deeper than the other three Gulf and Caribbean species. *A. stewarti* does overlap the lower half of the depth distributions of the other three; however, it is the only species that has not been taken shoaler than 200 fm. (366 m.).

Habits

We have little information on this species. It has been taken only with a bottom trawl; however, we have no information on bottom type or temperature. Specimens are most often taken singly; however, we have one collection with six fishes. *A. stewarti* has been taken with *georgei* and *brucei*.

Name

Named for Stewart Springer in recognition of his numerous contributions to the ichthyology of the tropical western Atlantic.

Study Material

All from the Atlantic. Holotype; USNM 202996, 144 mm. standard length; *Oregon* 3565, 14°10′ N.,

1°55′ W., 240 to 250 fm. (439–457 m.), May 21, 962. Paratypes:

Central America.—USNM 203572 (1 specimen); *regon* 3610, 12°23′ N., 82°29′ W., 200 fm. (366 .). USNM 202998 (4); *Oregon* 3574, 12°31′ N., 2°21′ W., 200 fm. (366 m.). USNM 188223 (1); *regon* 3614, 14°00′ N., 81°50′ W., 200 fm. (366 .). USNM 202997 (1); USNM 187790 (6); *regon* 3565, data as for holotype.

Antilles.—MCZ (1); *Oregon* 5925, 15°38′ N., °15′ W., 245 fm. (448 m.). FMNH 66225 (1); *regon* 2636, 17°37′ N., 63°36′ W., 280 fm. (512 .). USNM 202999 (2, 1 cleared and stained); *regon* 6695, 17°41′ N., 62°50.5′ W., 300 to 320 h. (549–585 m.). USNM 186356 (1); *Oregon* 45, 18°12′ N., 67°42′ W., 260 fm. (476 m.). MNH 66226 (1); *Oregon* 2651, 18°16.5′ N., °17′ W., 250 fm. (457 m.). USNM 108374 (1); *roline*, 18°32′ N., 68°21′ W., 260 fm. (476 m.). MNH 66224 (2); *Oregon* 2606, 18°37.5′ N., °04′ W., 210 fm. (384 m.).

ARGENTINA BRUCEI, NEW SPECIES

Figures 2, 3, 4, 5, 8, 9, 10D, 13

Argentina striata not of Goode and Bean, 1896; ohen, 1964 (fig. 5).

agnosis

A. brucei differs from *sphyraena* and *silus* in aving smooth instead of spiny scales and five in- ead of six branchiostegal rays. It differs from *lus*, *sialis*, *aliceae*, and *elongata* in having seven ometimes six) gill rakers on the lower arm of e first arch rather than eight or more. It differs om all *Argentina* except *sphyraena* and *aliceae* in its low vertebral count, 44 to 46 rather than 47 or more. It differs from *sphyraena*, *sialis*, *elongata*, *australiae*, and *kagoshimae* in having 18 to 20 pectoral rays rather than 19 or fewer. It differs from *elongata*, *kagoshimae*, and *euchus* in having 13 or 14 ventral rays rather than 12 or fewer. It differs from *australiae*, *kagoshimae*, *euchus*, *striata*, *georgei*, and *stewarti* in having usually seven gill rakers rather than usually six gill rakers. It differs from *striata* in usually lacking silvery pigment on the swimbladder.

Counts

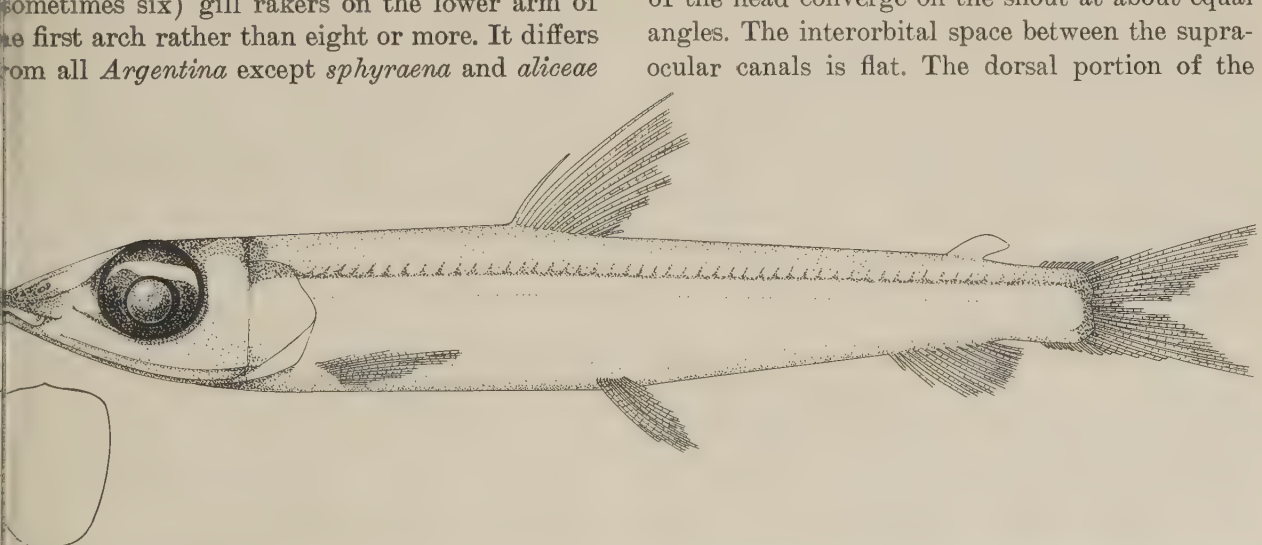
See tables 1 to 6.

Measurements

Based on about 72 specimens, 68.4 to 132 mm. standard length, given as percent of standard length: Preanal 84.5 (74.6–87.9); preventral 56.2 (52.9–58.8); predorsal 48.3 (44.4–50.7); head length 31.2 (27.7–33.1); snout 10.1 (8.7–11.2); eye 10.0 (7.9–11.6); maxillary length 5.9 (4.6–6.6); depth at dorsal fin 13.0 (10.9–15.4); depth at caudal peduncle 5.9 (5.0–6.5).

Description

A relatively short-bodied species with greatest depth at dorsal origin tapering to caudal peduncle. Body in cross section deeper than wide, the venter broadly rounded. Body in preserved specimens notably soft. The head, when viewed laterally, usually has its dorsal profile broken by the upper margin of the eye. The dorsal and ventral profiles of the head converge on the snout at about equal angles. The interorbital space between the supraocular canals is flat. The dorsal portion of the



GURE 13.—*Argentina brucei*, USNM 159357, paratype, 128 mm. standard length. Scales not shown. Cross section from in front of dorsal fin. From Cohen, 1964, as *A. striata*.

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maxillary lies under the lachrymal. The distal end of the maxillary extends at least to the midpoint of the snout and in some specimens farther. The jaws are broadly rounded; the lower, which often has a slightly bony protuberance at the symphysis, is included. The palatine and the head of the vomer bear small, closely spaced, needlelike teeth, in a continuous band 2 to 5 teeth wide, about 55 on the head of the vomer and 70 on each palatine; no dentary teeth. The ceratobranchial of the fifth gill arch bears 8 small, conical teeth; two patches of similar teeth, 10 on the anterior patch and 14 on the posterior patch, are found at the anterior end of the fourth suprabranchial. The tongue bears eight strong, recurved teeth (description of dentition based on a single alizarin specimen). The gill rakers are medium-sized, widely spaced, and compressed at the base. The longest gill rakers are equal to one-seventh to one-eighth of the interorbital distance.

The pectoral fin originates on the dorso-lateral curve of the body close to the level of the posterior margin of the opercle. The distance between the innermost rays of the pectoral fins is generally less than the least depth of the caudal peduncle. The pectoral fin extends at least half the distance from the pectoral origin to the ventral fin origin.

The scales are deciduous and lack spines. Scale pocket counts are difficult on this soft-bodied fish; however, we estimate about 48 lateral line scales.

The peritoneum is peppered with large, dark chromatophores; however, they are not so densely distributed that they give the peritoneum a completely black appearance. The gut is immaculate. Eight to 10 pyloric caeca are present in 12 specimens; many body cavities are heavily invested with fat. The swimbladder usually begins slightly anterior to the hind curve of the stomach and terminates slightly beyond the origin of the ventral fins. Six specimens of about one hundred had silvery swimbladders; otherwise, bladders lack pigment.

Pigmentation of adult specimens preserved in formaldehyde solution is a light straw color below the lateral line, somewhat darker along the upper third of the body. The duskiness is not continuous over the dorsum. Many examples carry 8 to 12 indistinct dusky blotches on the upper part of the body. The throat, breast, and belly are unpigmented (fig. 10), although a few specimens have a light sprinkling of chromatophores at the bases of the pectoral and ventral fins. The peritoneum shows through the midventral line in some specimens.

Distribution

A. brucei has been taken on the north coasts of Hispaniola and Puerto Rico; off Jamaica, Honduras, Nicaragua, Costa Rica, and Panama; and along the north coast of South America. It has also been trawled at several localities off the mouths of the Orinoco.

Depth distribution ranges from 100 to 300 fm. (183–549 m.); however, the fish has been most often caught between 100 and 230 fm. (183–421 m.).

Habits

A. brucei has been taken only with a bottom trawl, over a mud bottom, at bottom temperatures ranging from 50° to 64° F. (10°–17.8° C.). The fish is caught more often in aggregations than singly. *A. brucei* has been taken in mixed collections with all three of the other tropical western Atlantic species, *striata*, *georgei*, and *stewarti*, though with only one at a time.

Name

Named for the well-known ichthyologist Bruce B. Collette, who helped collect many of the specimens upon which this description is based.

Study Material

All from the Atlantic. Holotype: USNM 203029, 117 mm. standard length; *Oregon* 3584, 9°13′ N., 81°30′ W., 200 fm. (366 m.), May 25, 1962. Paratypes:

Central America.—USNM 187817 (3 specimens), *Oregon* 3595, 9°02′ N., 81°26′ W., 100 fm. (183 m.). USNM 187789 (16) and TABL 100571 (6); *Oregon* 3598, 9°03′ N., 81°22′ W., 200 to 220 fm. (366–402 m.). USNM 203047 (5); *Oregon* 3597, 9°04′ N., 81°25′ W., 150 to 160 fm. (274–293 m.). USNM 187833 (7); *Oregon* 3585, 9°12′ N., 81°30′ W., 135 to 140 fm. (247–256 m.). USNM 187837 (1); *Oregon* 3584, data as for holotype. USNM 187753 (1); *Oregon* 3590, 9°18′ N., 80°22′ W., 125 fm. (229 m.). USNM 200429 (5, 1 cleared and stained); *Oregon* 5738, 9°14′ N., 79°07′ W., 120 fm. (220 m.). USNM 188016 (5); *Oregon* 3610, 12°23′ N., 82°29′ W., 200 fm. (366 m.). USNM 203031 (4); *Oregon* 3574, 12°31′ N., 82°21′ W., 200 fm. (366 m.). USNM 187793 (7); *Oregon* 3570, 14°08′ N.,

1°55′ W., 200 to 240 fm. (366–439 m.). TABL 00566 (1); *Oregon* 3615, 14°16′ N., 81°55′ W., 00 fm. (366 m.). USNM 185093 (1) and FMNH 571 (3); *Oregon* 1868, 16°36′ N., 82°37′ W., 175 n. (320 m.). USNM 159353 (1); *Oregon* 1871, °39′ N., 82°26′ W., 250 fm. (457 m.). ANSP 604 (14); *Oregon* 3626, 16°45′ N., 81°27′ W., 0 fm. (274 m.). TABL 100562 (3); *Oregon* 3627, °50′ N., 81°21′ W., 200 fm. (366 m.). FMNH 218 (2); *Oregon* 1883, 16°52′ N., 81°30′ W., 200 n. (366 m.).

South America.—USNM 159356 (3); FMNH 222 (2); *Oregon* 1985, 9°41′ N., 59°47′ W., 0 fm. (274 m.). USNM 159357 (9) and UF 8026); *Oregon* 1989, 9°45′ N., 59°45′ W. UF 5237 (6) d FMNH 66221 (6); *Oregon* 1983, 9°43′ N., °53′ W., 125 fm. (229 m.). USNM 203049 (1); egon 4465, 10°45′ N., 66°37′ W., 125 fm. (229). USNM 203032 (1); *Albatross* 2700, 10°59′ N., °00′ W., 140+ fm. (256+ m.). MCZ 45937 (6); egon 4838, 11°09.5′ N., 74°24.5′ W., 170 to 180 . (311–329 m.). TABL 100568 (1); *Oregon* 4858, °09′ N., 74°25′ W., 160 fm. (293 m.). USNM 8973 (2); *Oregon* 4860, 11°09′ N., 74°26′ W., 5 to 160 fm. (284–293 m.). USNM 203033 (1); egon 4410, 11°52′ N., 69°27′ W., 230 fm. 21 m.). USNM 203048 (2); *Oregon* 4408, 11°53′ , 69°28′ W., 230 fm. (421 m.). USNM 203030); *Oregon* 4407, 11°59′ N., 69°30′ W., 230 fm. 21 m.).

Antilles.—TABL 100570 (4); USNM 187838 4); *Oregon* 3549, 17°50′ N., 77°52′ W., 170 fm. 11 m.). USNM 186355 (1) and FMNH 66227); *Oregon* 2653, 18°18′ N., 67°18.5′ W., 300 fm. 49 m.). USNM 186354 (1); *Oregon* 2656, 18°24′ , 67°15′ W., 100 fm. (183 m.). MCZ 40588 (4); MNH 66228 (5); *Oregon* 2658, 18°26′ N., 67°11.5′ ., 175 fm. (320 m.). USNM 186352 (2); *Oregon* 64, 18°31.5′ N., 66°46.5′ W., 160 fm. (293 m.). SNM 186353 (1); *Oregon* 2665, 18°31.5′ N., °50′ W., 180 fm. (329 m.). USNM 186357 (1) d FMNH 66229 (1); *Oregon* 2666, 18°32′ N., °46.5′ W., 200 fm. (366 m.). TABL 100565 (2); *lver Bay* 5161, 19°57′ N., 71°05′ W., 190 fm. 8 m.).

ARGENTINA EUCHUS COHEN

Figure 2

A. euchus was originally described from only wo specimens (Cohen, 1961). On the basis of an dditional 15, we here present a new diagnosis and counts and measurements as well as a range extension.

Diagnosis

A. euchus differs from *sphyraena* and *silus* in its smooth instead of spiny scales and by its five instead of six branchiostegals. It differs from *sphyraena*, *silus*, *sialis*, *aliceae*, *elongata*, and *brucei* in having six gill rakers on the lower arm of the first arch rather than seven or more. It has 47 or 48 vertebrae, more than *aliceae* and *brucei*, which have 43 to 46; and fewer than *silus*, *elongata*, *australiae*, *kagoshimae*, and *stewarti*, which have 49 to 67. It differs from *sialis* and *australiae* in having 16 to 18 pectoral rays rather than 11 to 14. It differs from *silus*, *striata*, *georgei*, *brucei*, and *stewarti* in having 10 or 11 ventral rays rather than 12 or more.

Counts

See tables 1 to 7.

Measurements

Based on 14 specimens, 123 to 154 mm. standard length, given as percent of standard length. Preanal 82.4 (81.2–83.6); maxillary width 1.6 (1.4–1.8); depth at dorsal fin 13.5 (11.9–15.3); head depth 12.9 (11.7–13.8).

Discussion

The measurements given above were used, on the basis of the two types, to help separate *A. euchus* from *A. elongata*, *australiae*, and *kagoshimae* (Cohen, 1961). The additional material herein reported upon shows that with the exception of body depth and head depth in separating *euchus* from *australiae*, morphometric data are unsatisfactory in diagnosing *A. euchus*.

Four specimens examined lacked silvery pigment or iridescence on their swimbladders.

Distribution

A. euchus has been taken off Natal, southern Mozambique, and Kenya at depths ranging from 131 to 322 fm. (240–589 m.).

Study Material

All from the western Indian Ocean. USNM 203160 (1 specimen), *Anton Bruun* cruise 8, sta. 421 G, 02°56′ S., 40°28′ E. 240 m. USNM 203159 (11), MCZ (1), FMNH (1), and BMNH (1); *Anton Brunn* cruise 8, sta. 396 B, 25°32′ S., 33°24′ E., 450 to 455 m.

GENUS *GLOSSANODON* GUICHENOT

We have received material of *Glossanodon polli* from West Africa and five small fishes from the Arabian Sea that represent a species close to but distinct from *G. polli.*

GLOSSANODON MILDREDAE, NEW SPECIES

Figure 14

Diagnosis

G. mildredae differs from *pygmaeus* in having its vent immediately anterior to the anal fin base rather than farther forward, in having teeth on the dentary, and in having 23 rather than 12 to 14 pectoral rays. It differs from *leioglossus* and *semifasciatus* in having dentary teeth along more than half the distance from the symphysis to the angle of the gape. It differs from *lineatus* in having 5 instead of 4 branchiostegal rays, 13 instead of 15 anal rays, and 23 instead of 20 pectoral rays. It differs from *polli* in having at least 55 lateral line scales rather than 48 to 51. Also, *G. mildredae* has dusky blotches mainly above the midline of the body; in similar-sized *polli*, the ventral half of the side bears continuations of the dorsal blotches.

Counts and Measurements

See table 8.

Description

Greatest depth behind head, tapering little to caudal peduncle. The dorsal profile of the head is slightly interrupted by the dorsal rim of the orbit. The ventral profile of the head rises more abruptly from a point below the anterior margin of the eye. The interorbital space between the supraocular canals is flat.

The dorsal margin of the maxillary lies under the lachrymal and extends to the joint between the lachrymal and the jugal; its distal end is closer to the anterior margin of the orbit than to the snout. Lower jaw projecting slightly; both jaws are rounded, the lower less broadly.

TABLE 8.—*Counts and measurements in millimeters on type specimens of* Glossanodon mildredae

	Holotype USNM 203235	Paratype USNM 203234	Paratype USNM 203234	Paratype USNM 203234	Paratype USNM 203233
Measurements:					
Standard length	64.9	69.8	58.1	65.7	41.6
Preanal	54.1	"	48.6	53.6	32.2
Preventral	33.5	"	29.5	34.1	22.7
Predorsal	30.7	"	28.4	31.3	20.7
Head length	20.8	"	16.6	19.2	13.7
Snout	6.2	"	5.1	4.7	4.1
Eye	6.2	"	5.4	6.4	3.9
Maxillary length	5.3	"	4.0	4.6	3.1
Maxillary width	1.2	"	1.0	1.2	"
Body depth at dorsal	7.1	"	6.2	7.7	5.4
Body width behind head	7.0	"	5.3	6.5	4.2
Caudal peduncle depth	4.1	4.3	3.8	4.2	3.1
Counts:					
Dorsal fin rays	13	"	13	13	"
Anal fin rays	13	13	13	13	"
Pectoral fin rays	23	"	"	23	23
Ventral fin rays	13	12	12	12	13
Vertebrae	51	50	50	51	49
Gill rakers on lower arm first arch	"	23	23	"	"
Lateral line scales	55+	"	"	"	"
Branchiostegal rays	"	5	5	5	"

Each palatine bears 15 to 20 short, conical, widely spaced teeth, arranged in an irregular series. The head of the vomer has 10 to 12 similar teeth. The tongue lacks teeth. About 10 teeth are widely spaced in a single irregular row on each dentary, extending from the symphysis to the angle of the gape. The gill rakers are elongate, lathlike structures and are closely spaced on the gill arch. The longest rakers equal about one-half the interorbital distance.

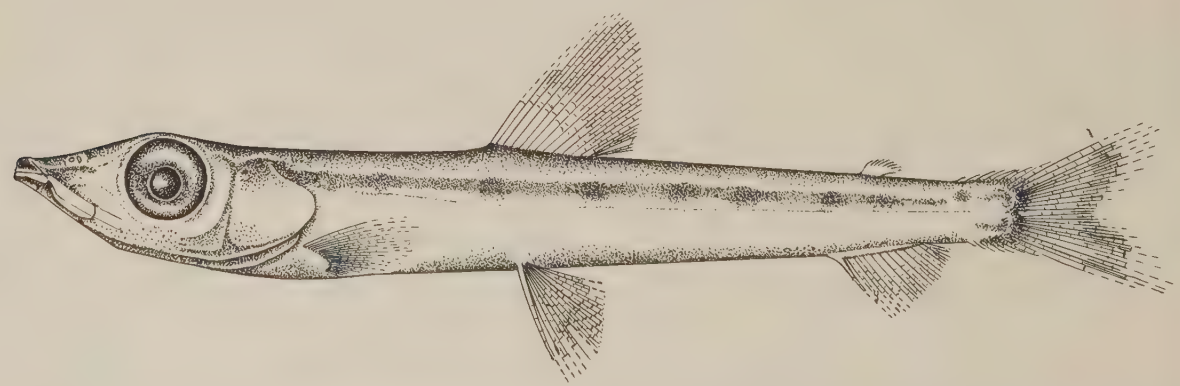

FIGURE 14.—*Glossanodon mildredae*, USNM 203235, holotype, 64.9 mm. standard length. Scales not shown. Drawn by Mildred H. Carrington.

The posterior end of the pectoral fin base forms n angle of 35 to 40 degrees with the horizontal. The tip of the pectoral fin extends at least one-hird of the distance from the pectoral fin origin o the ventral fin origin. The ventral may be some-what longer. The longest rays of the dorsal fin are onger than body depth.

Scales are lost from all four specimens; how-ver, on the holotype we have been able to count t least 55 scale pockets along the lateral line and here are possibly 4 or 5 more.

The peritoneum is dusky. The gut is immaculate. The swimbladder lacks silvery pigment. Nine py-oric caeca are present in a single specimen.

The largest paratype (69.8 mm. standard ength) has gonads containing minute, transparent ggs. We cannot say whether this fish is an im-ature female or a mature female with unripe onads. If the latter, then *G. mildredae* matures at smaller size than does *G. polli*.

The body is straw-colored, with a narrow brown and extending along the side above the midline. paced along the band, and broader but less well efined is a series of 8 to 10 dusky blotches, which re less distinct anteriorly. The blotches extend arely below the midline of the body. In our small-st specimen (41.6 mm. s.l.) the blotches are made f large, widely spaced chromatophores and the teral band is very indistinct. *G. polli* of sizes omparable with our *mildredae* specimens (See g. 8 in Cohen, 1958, taken from Poll, 1953, of a ecimen 8.3 cm., probably fork length. Also SNM 203244, 61.5 mm. standard length and SNM 203243, 65.8 mm. standard length) have lotches or bands over the ventral as well as the orsal half of the side.

iscussion

G. mildredae is closest to *G. polli*, from which it s not easily distinguished. Unfortunately, our ma-erial of *G. mildredae* is limited in quantity, size, nd quality, and we have but few specimens of *. polli* of comparable size. We doubt that one and he same species of *Glossanodon* lives in the tropi-al western Indian Ocean and off tropical West frica, and we believe that at least the characters n our diagnosis serve to indicate the existence of wo distinct populations.

istribution

Known only from two localities in the tropical estern Indian Ocean.

Name

Named for Mildred H. Carrington, whose taste-ful and accurate drawings have contributed greatly to the progress of ichthyology.

Study Material

Holotype: USNM 203235, 64.9 mm. standard length, *Anton Bruun* cruise 9, sta. 422, 6°51′ S., 39°54′ E., 54 fm. (99 m.); 19 Nov. 1964; bottom trawl. Paratypes: USNM 203234 (3 specimens); data as for holotype. USNM 203233 (1); *Anton Bruun* cruise 9, sta. 463, 11°24′ N., 51°35′ E., 41 to 95 fm. (75–174 m.), 17 Dec. 1964, bottom trawl.

GLOSSANODON POLLI COHEN

G. polli has not been recorded since its original description (Cohen, 1958). We have examined the 18 recently collected specimens listed below and find that they agree well with the description. The two *Geronimo* specimens listed below are juveniles of 61.5 and 65.8 mm. standard lengths and show the barred pattern illustrated in the original description.

Study Material

USNM 203236 (12 specimens), MNHN (2), MCZ (1), and FMNH (1); Guinean Trawling Survey, *La Rafale*, transect 8, sta. 6, 8°28′ N., 14°21′ W., 55 fm. (100 m.). USNM 203244 (1), *Geronimo* cruise 2, sta. 213, 2°31′ S., 8°51′ E., 110 fm. (201 m.). USNM 203243 (1), *Geronimo* cruise 2, sta. 214, 2°01′ S., 8°50.5′ E., 110 fm. (201 m.)

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BATHYMETRIC MAPS AND GEOMORPHOLOGY OF THE MIDDLE ATLANTIC CONTINENTAL SHELF

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ABSTRACT

Large-scale bathymetric maps covering the northern two-thirds of the Middle Atlantic Continental Shelf have recently been published. They were compiled at a scale of 1:125,000 from 39 smooth sheets and are contoured in 1-fm. (1.8 m.) intervals on the shelf and in 10-fm. (18.3 m.) intervals on the upper slope.

Part 1 of this report discusses the construction and reliability of these maps. In addition, a short review of surveys made in the mapped area is given, a few uses for the maps are suggested, and the reliability diagrams (which appear on each map) are explained.

Part 2 discusses the past geologic history, the general distribution of sediments, and the major geomorphic processes at work in the area. In addition, the several physiographic regions and features on the Middle Atlantic Shelf are described in terms of their topography and sediments.

The Middle Atlantic Continental Shelf is one of the world's most studied shelf areas. The 60,000 square nautical miles[1] of drowned coastal lowland making up its surface have long been of interest to mariners, commercial fishermen, and scientists. Numerous nautical chart surveys, oceanographic studies, and geophysical, geological, and biological investigations have been made in the area (Geyer, 1948; Drake, Ewing, and Sutton, 1959; Heezen, Tharp, and Ewing, 1959; Murray, 1961; Drake, Heirtzler, and Hirshman, 1963; Stearns, 1963; Uchupi, 1963; Livingstone, 1965; and Emery, 1966b).

The Middle Atlantic Continental Shelf borders one of the world's largest concentrations of human activity. Called Megalopolis by Gottmann (1961), this region contains almost one-fifth of the population of the United States and is a vast market for marine resources of all kinds. The shelf supplies Megalopolis with commercial and sport fisheries, recreation on the seashores, mineral resources, and space for waste disposal. The need for detailed bathymetric maps in the study of Continental Shelf geology, geomorphology, and mineral resources is well known (Veatch and Smith, 1939; Emery and Schlee, 1963; Emery, 1966b). Less widely appreciated, but equally important, are the uses of such maps in the synthesis and study of physical and biological data.

The shape of the sea floor can influence the movement of water masses on the shelf, and this movement can affect the distribution of such oceanographic properties as temperature, salinity, and nutrient elements (Bigelow, 1931; Hachey, Lauzier, and Bailey, 1956; Trites, 1956). Although only a few benthonic animals are known to respond directly to the shape of the bottom (e.g., see Yonge, 1962), all marine animals respond to the distribution of water-mass properties, which are affected by the bottom. Hence, definite correlations exist between the shape of the bottom and the locations of marine animals (see Parker and Curray, 1956), and detailed studies of environmental relations on the shelf require a detailed knowledge of bathymetry.

[1] I use English fathoms and nautical miles throughout the paper because all the data were collected in English rather than metric units. For conversion, 1 fm. equals 1.83 m., and 1 nautical mile equals 1.85 km.

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Large-scale bathymetric maps covering the northern two-thirds of the Middle Atlantic Continental Shelf (fig. 1) have recently been published by Stearns and Garrison (1967). These maps are contoured in 1-fm. intervals from the shore to 100 fm. and in 10-fm. intervals from 100 to 500 fm. and are drawn on a Mercator projection at a nominal scale of 1 : 125,000.

The present maps can be used in a variety of ways, such as (1) interpolation aids when mapping physical data, (2) foundations for the analysis of relations between physical features and biological distributions, and (3) sources of information for the efficient planning of stratified sampling programs and surveys.

The purpose of this paper is to describe these maps, their construction and reliability, and to discuss the geomorphology of the mapped region.

PART 1. BATHYMETRIC MAPS

The proper use of bathymetric maps requires some knowledge of how they were made, as well as an estimate of their reliability. These topics are discussed in this part of the report.

FIGURE 1.—Generalized bathymetry of the Middle Atlantic Continental Shelf and locations of major features discussed in the text. Depth contours in fathoms. Sources: USCGS Chart 1000 (13th ed., 1949) and Stearns and Garrison (1967).

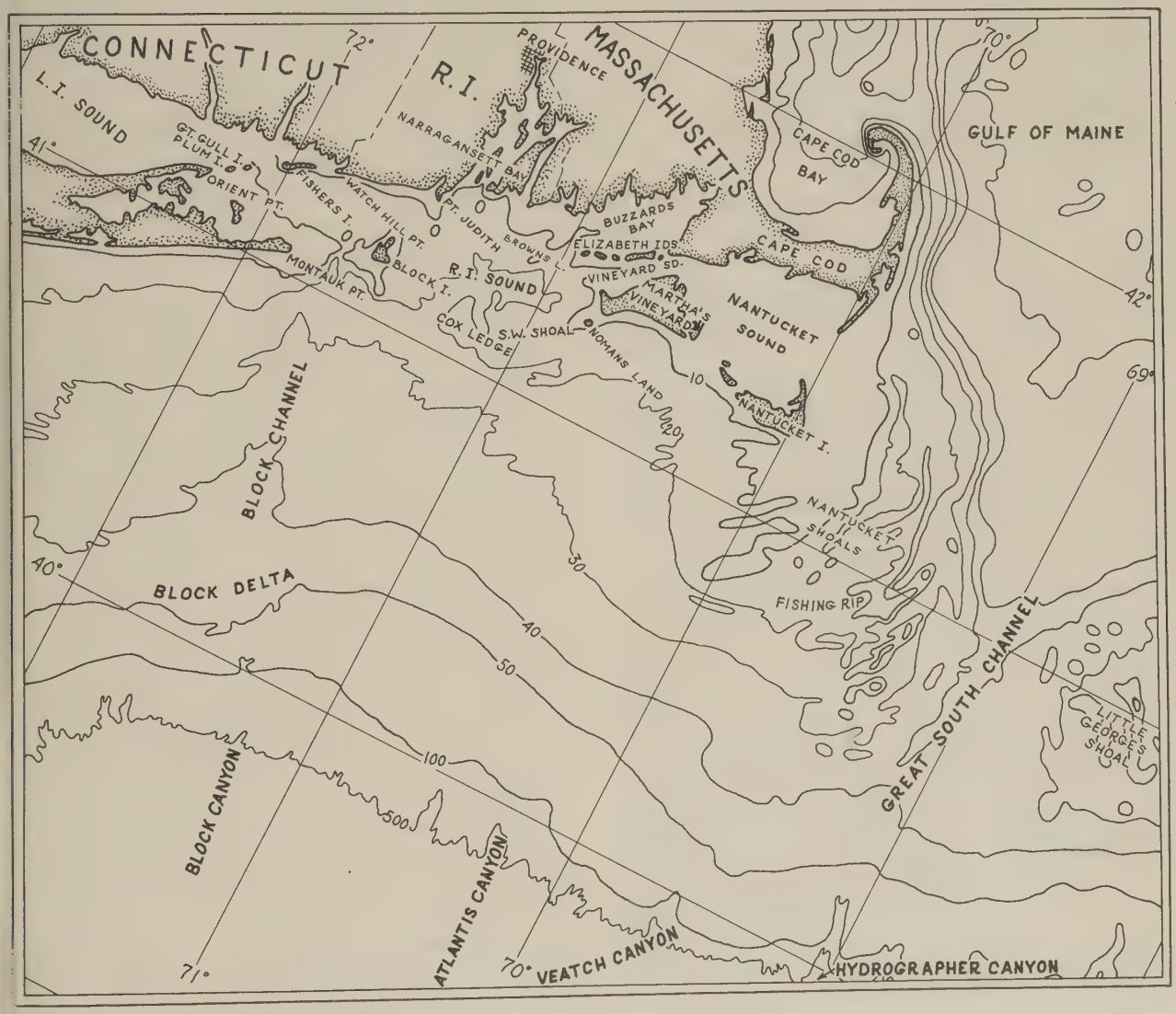
CONSTRUCTION OF THE MAPS

Construction of the maps is discussed from three aspects: (1) history of past surveys, (2) study of present surveys, and (3) methods of construction.

Past Bathymetric Surveys

The first systematic bathymetric survey of the entire width of the Middle Atlantic Continental Shelf was made by the U.S. Coast Survey in 1842 (USCGS Hydrographic Survey no. 100, scale 1:400,000). Previously, only some inshore areas had been systematically surveyed, and charts of the offshore regions were based on a few isolated soundings. The 1842 survey covered the area between Rhode Island Sound and Cape May and from near shore to a little over 100 fm. It was supplemented in 1844 by a survey covering much the same area (no. 101, scale 1:400,000) and again in 1859 by a survey extending from Martha's Vineyard to slightly south of Cape Henlopen, Del. (no. 670, scale 1:400,000).

No surveys were made during the Civil War, but in the 1870's and 1880's much sounding was



done on the Continental Slope and in the adjacent ocean basins, largely as a result of (1) an increased interest in the life of abyssal regions, (2) increasing activity in the laying of submarine telegraph cables, and (3) the development of deep sea wire-sounding machines (Agassiz, 1888; Tanner, 1897). From 1877 to 1880 Alexander Agassiz (1888) directed surveys aboard the Coast Survey ship *Blake* along the Atlantic Continental Slope, but it was not until 1882 that the shelf itself was again surveyed, this time from Montauk Point, Long Island, to Cape Henlopen, Del. (no. 1558, scale 1:300,000). This survey was extended south to Cape Charles in 1886 (no. 1720, scale 1:200,000) and to the east as far as Georges Bank during 1887–1889 (nos. 1782, scale 1:300,000; and 1837, scale 1:400,000). In all of these early surveys, the soundings were by lead line and the navigation was by shore sightings, astronomical fixes, and dead reckoning.

Except for a few isolated investigations of shoal areas, the Middle Atlantic Shelf was not again systematically surveyed until the 1930's, when new sounding and navigational methods had been developed. These surveys, from Georges Bank to Cape Henry and from the shore to the Continental Slope and Rise, are the principal sources used for constructing the maps discussed in this paper.

Several earlier bathymetric maps were based on the surveys of the 1930's. The first and most famous are the maps of Veatch and Smith (1939)—see also Smith (1939). These authors compiled a series of charts of the Continental Slope from Georges Bank to Chesapeake Bay and of the Hudson Channel region of the shelf (scale 1:120,000). Uchupi (1965), in cooperative work by the Woods Hole Oceanographic Institution and the U.S. Geological Survey, used the surveys to compile a 1:1,000,000 scale map of the shelf, slope, and rise from southern Canada to the Straits of Florida. In addition, the USCGS has used the surveys to construct nautical charts of the region at scales of 1:80,000 and 1:400,000 (see the 1100 and 1200 series of nautical charts). The surveys have also been used for small maps, published as text illustrations (e.g., Elliott, Myers, and Tressler, 1955; Garrison and McMaster, 1966).

Present Data Sources

The data from 39 USCGS hydrographic surveys, made between 1932 and 1961, were used for making the present maps. (The smooth sheets of these surveys vary in scale from 1:20,000 to 1:120,000.) In addition, 25 published USCGS nautical charts (scales 1:10,000 to 1:80,000) were used for some nearshore areas, bays, sounds, and harbors. The land contours which appear on some sheets were compiled from U.S. Geological Survey and Army Map Service topographic quadrangle maps (scales 1:24,000 and 1:62,500). The Long Island contours are from a topographic map of the Island, scale 1:125,000, appearing in Fuller (1914).

More bathymetric information exists than was used in the present compilation. Many miles of sounding lines have been run on the Middle Atlantic Continental Shelf by the research ships of various government agencies, private research institutions, and universities. Many of these data are equal in quality to those used, but most have not been reduced and plotted in a form that can be readily contoured.

The new developments in the surveys of the 1930's were echosounding and radio-acoustic ranging. Echosounding was developed in both the United States and Europe during the first part of this century, and by 1923 the USCGS had installed their first echosounder. This method of measuring depths was rapidly improved and soon replaced the older lead line and wire-sounding machine. Before the 1930's, positions were determined in much the same manner as they were in 1842 and before. During the early 1920's, offshore positioning had developed into an elaborate system of precise dead reckoning, but it was not until the USCGS introduced radio-acoustic ranging in 1924 that methods of navigation were changed fundamentally (Adams, 1942). This new method was continually improved throughout the surveys of the 1930's and was replaced by wholly electronic systems during the 1940's.

Methods of Construction

Bathymetric contour lines were drawn directly on either (1) full-scale, corrected copies of the original surveys (smooth sheets), or (2) on nautical charts of nearshore areas. Louis E. Garrison contoured the area between about long. 69°25′ and 72°00′ W. and shallower than about 100 fm. (US CGS Hydrographic Surveys 6331, 6347, 6440, 6441, and 6447). I contoured the rest of the area.

This contoured source material was transferred

by pantograph to dimensionally stable plastic compilation sheets at a uniform scale of 1:125,000 (Mercator projection, scale of 1:125,000 at lat. 40° N.); each sheet covered 1° of latitude and longitude. Transfer was done in stages for each piece of source material; small quadrangles were transferred independently to minimize distortion of scale and paper. Adjustment and matching between surveys, corrections, and final smoothing of the isobaths were done on the compilation sheets. The USCGS made the final map layout and design.

RELIABILITY OF THE MAPS

Present technology makes it impractical to observe large areas of the sea floor directly; thus, bathymetric maps are necessarily interpretive drawings of an invisible surface (for discussions of this subjective element in bathymetric mapping see Veatch and Smith, 1939; Jones, 1941; and Shepard, 1943). Such maps are usually made from discrete soundings, between which assumed depths must be interpolated before contour lines of constant depth (isobaths) can be drawn. The uncertainty of these assumed depths, plus observational and positional errors in the original soundings, makes exact correspondence between a bathymetric map and the real sea floor an impossibility. The user of a map, however, should know what accuracy to expect.

The following paragraphs of this section discuss the evaluation of the reliability of the maps, the reliability diagrams which appear on each map, and the spatial distribution of the map errors.

A general method for quantitative estimate of the reliability of isoline maps has been presented by Stearns (1968). In this general method the reliability of isolines (expressed as a variance) is related to (1) observational errors, (2) positional errors, (3) interpolation errors, (4) errors in the time of an observation, (5) synopticity errors (errors due to lack of simultaneity in the observations), and (6) the space-time rates-of-change and the directions of the gradients of the mapped variable.

In applying the method to the present bathymetric maps, I considered all the above factors, with the exception of time and synopticity errors. I omitted the time-dependent errors, first, because little exact information is available on the rates-of-change of bottom topography, and, second, because such changes, except in limited areas, are likely to be very small during the period of useful life of the maps.

The reliability equations (Stearns, 1968), with the time-dependent terms omitted, are as follows:

$$\bar{\epsilon}_3=\bar{e}_0+\bar{e}_p\bar{g}_p\,\overline{\mathrm{Cos}}\,\gamma_p+\bar{e}_l\bar{g}_l\,\overline{\mathrm{Cos}}\,\gamma_l+\bar{e}_l'\bar{g}_l'\,\overline{\mathrm{Cos}}\,\gamma_l' \tag{1}$$

which expresses the expected bias of the values of the isobaths at any point on the map or within any subarea of the map, and

$$\begin{aligned}V_{\epsilon_3}=&V_{e_o}+V_{e_p}(V_{g_p}+\bar{g}_p^2)\,(V_{\mathrm{Cos}\,\gamma_p}+\overline{\mathrm{Cos}^2}\,\gamma_p)\\&+\bar{e}_p^2(V_{g_p}[V_{\mathrm{Cos}\,\gamma_p}+\overline{\mathrm{Cos}^2}\,\gamma_p]+\bar{g}_p^2V_{\mathrm{Cos}\,\gamma_p})\\&+V_{e_l}(V_{g_l}+\bar{g}_l^2)\,(V_{\mathrm{Cos}\,\gamma_l}+\overline{\mathrm{Cos}^2}\,\gamma_l)\\&+\bar{e}_l^2(V_{g_l}[V_{\mathrm{Cos}\,\gamma_l}+\overline{\mathrm{Cos}^2}\,\gamma_l]+\bar{g}_l^2V_{\mathrm{Cos}\,\gamma_l})\\&+V_{e_l}'(V_{g_l}'+\bar{g}_l'^2)\,(V_{\mathrm{Cos}\,\gamma_l}'+\overline{\mathrm{Cos}^2}\,\gamma_l')\\&+\bar{e}_l'^2(V_{g_l}'[V_{\mathrm{Cos}\,\gamma_l}'+\overline{\mathrm{Cos}^2}\,\gamma_l']+\bar{g}_l'^2V_{\mathrm{Cos}\,\gamma_l}')\end{aligned} \tag{2}$$

which expresses the variance of the values of the isobaths at any point, or within any subarea, on the map.

These equations may be evaluated for a map as a whole (in which case a single average reliability value would be obtained), or for any arbitrarily selected small portion of a map. For the present maps, the equations were evaluated for each adjacent unit area of 5 geographical minutes to a side. This unit area was selected as a compromise between the geographic diversity of the map's reliability and the time available for manual computation. Over 1,600 unit areas were involved in the evaluation.

Evaluation of the Reliability

The evaluation of the terms in equations 1 and 2 are discussed in this section.

Observational errors (e_o).—The echosoundings made during the surveys of the 1930's and used as the basis for constructing most areas of the present maps were evaluated by Veatch and Smith (1939)—see also Adams (1942). They concluded (p. 60) that the accuracy of these soundings was within 1 part in 100 for areas deeper than 100 fm. and within 1 part in 200 for areas shallower than 100 fm. To approximate maximum errors on the shelf proper, I used their larger estimate, 1

part in 100, for all depths (0 to 500 fm.) and for all surveys and nautical charts used in the compilation.

Because of lack of data on bias in the soundings, I assumed unbiased work; hence, $\bar{e}_o$ was taken to be zero. The variance of the observational errors was estimated by assuming that the errors are normally distributed and that the value, 1 part in 100, represents 99 percent of the total distribution (this assumption implies that systematic and personal errors have been removed from the data and that any reduction errors have a random distribution). Therefore,

$$\pm d/100 = \pm 2.576 \sqrt{V_{e_o}}; \text{ hence } V_{e_o} = 0.000015d^2$$

where the variable d equals the maximum depth, in fathoms, within each 5-minute unit area.

To account for round-off errors, I added a constant factor to each variance value. This factor was 0.083 fm. when the soundings were recorded to the nearest fathom and 0.0023 fm. when recorded to the nearest foot. I assumed a rectangular, or uniform, distribution of these errors; hence, the variance equals $E^2/3$ (see Weatherburn, 1961, p. 14), where E equals one half of the round-off interval.

Positional errors (e_p).—Veatch and Smith (1939) discussed the accuracy of positioning for the radio-acoustic ranging methods used in the surveys of the 1930's (see also Adams, 1942). They concluded (p. 65) that the accuracy was 1 part in 200 for distances less than 100 nautical miles from the control (reference) points used in a survey. To approximate a maximum estimate of positional errors, I used 1 part in 100 for all of the surveys (except for a few recent ones which cover a large part of Nantucket Shoals) and all the nautical charts.

Again, because of lack of data, I assumed unbiased work; hence $\bar{e}_p$ was taken to be zero. The variance of the positional errors was determined in the same way as described above for observational errors; hence $Ve_p = 0.000015D^2$, where the variable D equals the maximum distance in nautical miles between each 5-minute unit area and the nearest control point (sonobuoy or station vessel) used in a survey. For nearshore nautical charts the distance D was measured to the nearest prominent shore feature.

To each variance value I added a constant factor—0.0045 nautical mile, to account for such cartographic errors as paper distortion and misalignments in tracing and printing. This factor was calculated by assuming a normal distribution of cartographic errors with a 99 percent limit of ±0.1 inch or ±0.17 nautical mile at a scale of 1 : 125,000.

For the recent surveys on Nantucket Shoals (1959–61), during which electronic positioning systems were used, I assumed a 99 percent error of ±0.066 nautical mile (±400 feet) and a normal error distribution; hence $Ve_p = 0.0007$ nautical mile. To this was added the cartographic error variance of 0.0045 nautical mile giving a constant total error variance of 0.0052 nautical mile for these surveys.

Interpolation errors (e_l *and* $e_{l'}$).—If we were concerned with maps showing only the depths of soundings, the total error would be a simple combination of the positional and observational errors discussed above. Because, however, we are dealing with isobath maps, interpolation errors must also be considered. These errors are of two kinds: (1) those associated with depths interpolated along axes between actual soundings (primary interpolation error, e_l) and (2) those associated with depths interpolated between the primary interpolation axes (secondary interpolation error, $e_{l'}$).

The equations for computing these interpolation errors are (Stearns, 1968):

$$\bar{e}_l = \bar{e}_{l'} = 0 \tag{3}$$

$$V_{e_l} = \tfrac{1}{6}(V_l + \bar{l}^2) \tag{4}$$

$$V_{e_{l'}} = \tfrac{1}{6}(V_{l'} + \bar{l}'^2) \tag{5}$$

These are based on a simple two-point linear interpolation scheme.

The evaluation of V_{e_l} and $V_{e_{l'}}$ depends on the particular survey pattern used. The quantity $(V_l + \bar{l}^2)$ in equation 4 is the mean sum of the squares of the distances between the soundings. For a rectangular array of discrete soundings along more or less parallel track lines, as is the situation for most of the hydrographic surveys of the Middle Atlantic Continental Shelf, this quantity equals $\frac{1}{2}(a^2 + b^2)$, where a is the distance between track lines and b is the distance between soundings on each line. By taking the mean of five systematic samples of the two distances, I estimated the quantities a and b for each 5-minute unit area.

The quantity $(V_{l'}+\bar{l}'^2)$ in equation 5 is the mean sum of the squares of the distances between the primary interpolation axes. Several choices are possible for secondary interpolation axes (Stearns, 1968). The correct choices are those axes actually used by the cartographer in drawing the map. A human being, however, in his subjective approach to contouring, is seldom fully aware of just what axes he has used. Therefore, in computing the reliability of the present maps, I assumed that the shortest axes were used, which, in the rectangular trackline surveys of the Middle Atlantic Continental Shelf, equaled the distance between soundings. These distances are usually equal within any unit area, so the quantity $(V_{l'}+\bar{l}'^2)$ equals b^2.

The topographic slopes.—Positional and interpolation errors (which are expressed in distance units) are converted into depth errors, by multiplying them by g Cos γ, where g is the positive topographic slope in the vicinity of the soundings (or the interpolated point) and γ is the angle between the errors and the local slope.

The slopes g_p, g_l, and $g_{l'}$ were assumed to be equal and were estimated from five systematic samples taken in each 5-minute unit area. Each sample consisted of the maximum slope measured in a circle 1 nautical mile in diameter. The mean slope, $\bar{g}$, was taken as the mean of the five samples, and the variance of the slopes, V_g, was approximated by $(0.43\ \omega)^2$, where ω was the range of the five samples. This estimate of the variance assumed that the slopes have a normal distribution within each 5-minute unit area and was used as a computational expedient (see Dixon and Massey, 1957, pp. 273, 404).

The cosines.—In estimating the cosines in equations 1 and 2, I assumed that all angles had an equal probability of occurrence; thus γ_p, γ_l, and $\gamma_{l'}$ range from zero to π radians (from 0° to 180°), and the probability functions of the angles equal $1/\pi$. Hence,

$$\overline{\text{Cos}}\ \gamma=\frac{1}{\pi}\int_0^{\pi}\text{Cos}\ \gamma d\gamma=0$$

and

$$V_{\text{Cos}\ \gamma}=\frac{1}{\pi}\int_0^{\pi}\text{Cos}^2\gamma d\gamma=\tfrac{1}{2}$$

This assumption may be true for positional errors, because I assumed that these errors are unbiased. It is not strictly true, however, for interpolation errors, and a more accurate, although more time-consuming method could have been used; i.e., the final map could have been matched with the interpolation networks actually used and the angles measured.

The Source Diagram

The source diagram on each map shows the number, scale, and date of the USCGS hydrographic surveys and nautical charts used in the construction of the maps.

The maps depict the sea floor at the dates of the various surveys, and the user must draw his own conclusions as to changes that may have taken place since then. Significant changes are likely only along some portions of the coast above about 10 fm., in offshore shoal areas, and along the upper Continental Slope where slumping may have occurred (see Lucke, 1934a, 1934b; Howard, 1939; Heezen, 1963; Miller and Zeigler, 1964; Stewart and Jordan, 1964; Uchupi, 1967). In such areas the maps and their reliability diagrams should be used with caution.

Those who wish to study the actual soundings may examine or purchase copies of the original hydrographic survey sheets from the USCGS, Washington, D.C.

Diagram of the Mean Distance Between Track Lines

The mean distance between track lines is a common device for indicating the reliability of bathymetric maps. Reliability is usually assumed to be better where the lines are closely spaced. Trackline spacing also indicates the resolution of a survey; i.e., the minimum size of features consistently discoverable from the survey. Surveys with many different trackline spacings were used in drawing the maps. Consequently, the isobaths are more detailed in some areas than in others.

Diagram of the Standard Deviation of the Isobath Depth Error

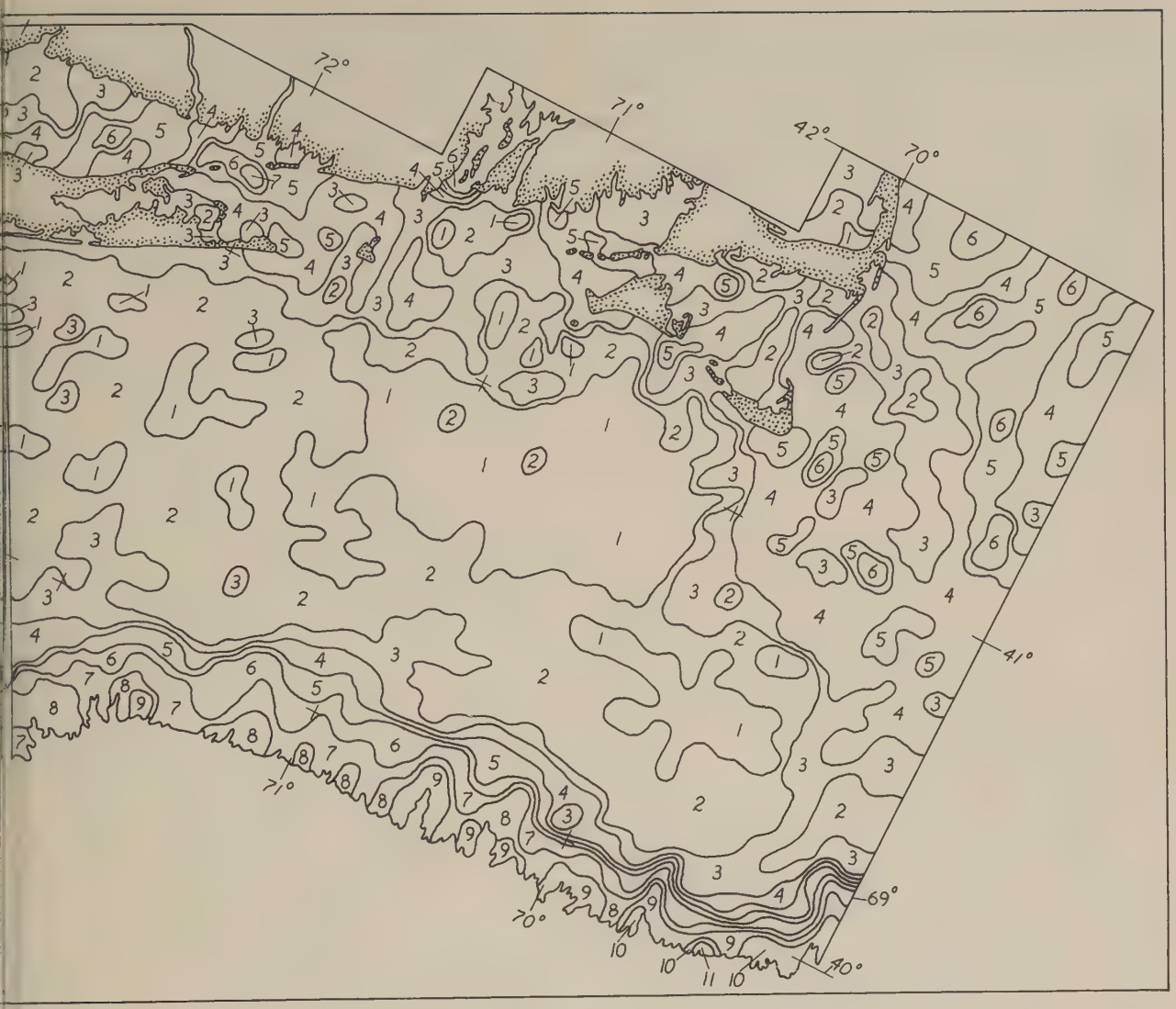
The standard deviations in the isobath depth error diagram are estimates of how much and how frequently the depths indicated on the maps may depart from the true depths. The diagram is based on the square root of the variance given by equation 2 and shows the average standard deviation in unit areas of 5 geographical minutes to a side. It applies to depths as indicated on the maps, not to the original soundings. A more detailed diagram of the entire mapped area is reproduced in figure 2.

FIGURE 2.—Standard deviation of the isobath depth error. (1) Less than 0.25 fm. (2) 0.25–0.49 fm. (3) 0.50–0.99 fm. (4) 1.00–1.99 fm. (5) 2.00–3.99 fm. (6) 4.00–7.99 fm. (7) 8.00–15.99 fm. (8) 16.00–31.99 fm. (9) 32.00–63.99 fm. (10) 64.00–127.99 fm. (11) 128.00 fm. and more.

The figures in the diagram may be used to estimate the expected correspondence between the mapped depths and the true depths. This expected correspondence is expressed as a probability that the true depth falls between certain limits. For example, if we assume a normal distribution of depth errors in an area where the standard deviation of the depth error is 1 fm., then the probability is 99 percent that the indicated depth is correct to within ± 2.6 fm., 90 percent that the depth is correct to within ± 1.6 fm., or 50 percent that the depth is correct to within ± 0.7 fm. The depth of any isobath as shown on the maps should be thought of as representing a probable range of depths rather than as a single exact depth.

The above limits were computed by the formula $r = Z_i \sigma$, where r is the expected range of depths, σ is the standard deviation taken from the depth error diagram (fig. 2), and Z_i is a number that depends upon the probability i and upon the kind of error distribution (see Dixon and Massey, 1957, or other statistics textbooks).

The above formula gives the expected range due only to errors in the map. To find the expected range when the maps are being used aboard a ship to search for a given bathymetric feature, the



standard deviation would have to include the ship's errors; i.e., $\sigma=\sqrt{\sigma_m{}^2+\sigma_s{}^2}$, where σ_m is the map standard deviation taken from the depth error diagram, and σ_s is the ship standard deviation. The ship standard deviation may be estimated as the square root of the first three terms on the right-hand side of equation 2.

Diagram of the Standard Deviation of the Isobath Position Error

The standard deviations in the isobath position error diagram are estimates of how much and how frequently the positions of the depths as indicated on the maps may depart from the true positions. This diagram is also based on the square root of equation 2; it shows the average standard deviation in 5-minute unit areas and applies only to indicated depths—not to the original soundings. The values in the diagram were computed by dividing the standard deviations of the isobath depth error (fig. 2) by $\sqrt{V_g+\overline{g}^2}$, where $\overline{g}$ is the mean topographic slope of the sea floor in a given 5-minute unit area, and V_g is the variance of the topographic slope within the same 5-minute unit area. A more detailed diagram of the entire mapped area is reproduced in figure 3.

The figures in this diagram may be used to esti-

mate the expected correspondence between the mapped positions of the depths and their true positions. This expected correspondence is expressed as a probability that the true position falls between certain limits. For example, if we assume a normal distribution of position errors in an area where the standard deviation of the position error is 0.2 nautical mile then the probability is 99 percent that a given depth will be found within ±0.5 nautical mile of its indicated position (i.e., will be found within a circle 1.0 nautical mile in diameter centered on the given depth), 90 percent that it will be found within ±0.3 nautical mile of its indicated position, or 50 percent that it will be found within ±0.1 nautical mile of its indicated position. The position of any isobath as shown on the maps should be thought of as the center of a probable range of positions rather than as a single exact position.

The above limits were computed by the same formula as was the probable range of depths, except that here r is the expected range of positions, and σ is the standard deviation taken from the position error diagram (fig. 3).

This computation also applies only to map errors. To find the expected range when the

FIGURE 3.—Standard deviation of the isobath position error. (1) 0.05–0.09 nautical mile. (2) 0.10–0.14 nautical mile. (3) 0.15–0.19 nautical mile. (4) 0.20–0.24 nautical mile. (5) 0.25–0.29 nautical mile. (6) 0.30–0.39 nautical mile. (7) 0.40–0.49 nautical mile. (8) 0.50–0.59 nautical mile. (9) 0.60–0.69 nautical mile. (10) 0.70–0.79 nautical mile. (11) 0.80–0.89 nautical mile.

naps are being used aboard a ship, σ must be quated to $\sqrt{\sigma_m^2+\sigma_s^2}$, where σ_m is taken from the osition error diagram, and σ_s is computed by ividing the first three terms on the right-hand de of equation 2 by $V_g+\overline{g}^2$, for the area in which he ship is working, and then taking the square pot of the quotient.

istribution of the Map Errors

The standard deviations of the isobath depth rror (fig. 2) generally increase in an offshore irection. Most of this increase is due to the steeper opographic slope on the outer shelf and upper ope which makes interpolation of depths between soundings less certain in these regions. A part of the increase is also due to a wider spacing between tracklines offshore.

Most of the large inshore standard deviations are also caused by locally steep topographic slopes (e.g., the Hudson Channel, Long Island Sound, Delaware Bay, and Nantucket Shoals); however, the large deviations east of Cape Cod are due both to wide trackline spacing and to steep slopes.

Figure 4 shows the percentage of the total variance of the depth error which can be attributed to observational, positional, and interpolation errors.

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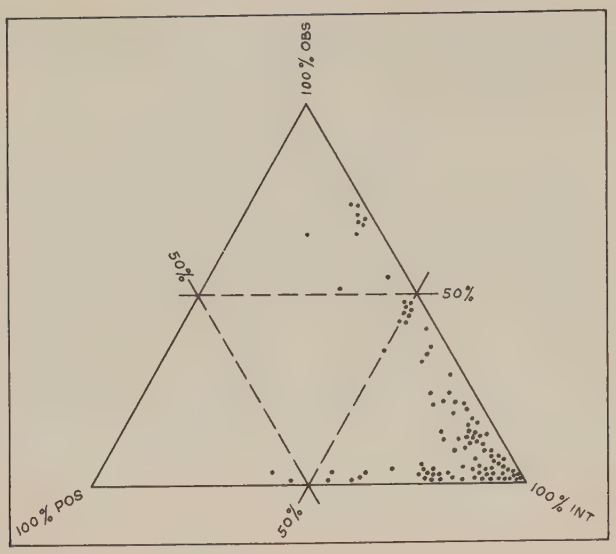

FIGURE 4.—Percentage of the variance of the isobath depth error that can be attributed to observational errors (OBS), positional errors (POS), and interpolation errors (INT).

The figure is based on the variance in 100 representative 5-minute unit areas. In most of these unit areas more than half of the total variance results from uncertainty in interpolations of assumed depths between the original soundings.

Interpolation errors are very sensitive to topographic slope and spacing between soundings. To achieve the same reliability of isobath depths, the spacing of soundings must be much closer in areas of steep slopes than in areas of gentle slopes. For many surveys, not only of bathymetry but of other variables as well, the observations are so widely spaced (usually for reasons of economy) that ordinary positional and observational errors have little effect on the reliability of the final isolines.

Figure 5 shows the relation of the standard deviation of the isobath depth error to the mean topographic slope in a few selected unit areas. The dispersion of the points results largely from variations in the spacing between tracklines.

The standard deviations of the isobath position error (fig. 3) also increase offshore, mostly because of wider spacing between tracklines. Figure 6 shows the relation of these standard deviations to the mean spacing between tracklines. The dispersion of the points is due mainly to variations in the observational and positional errors of the original soundings.

PART 2. GEOMORPHOLOGY

A description of the configuration of the Middle Atlantic Continental Shelf, along with a general discussion of its evolution, of the processes involved in its formation, and of its sediments, is presented in this part of the report.

GENERAL CONSIDERATIONS

The general appearance, geological history, sediment distribution, and geomorphic processes of the Middle Atlantic Shelf are discussed in this section.

General Appearance and Past Geologic History

The present continental border of eastern North America can be divided into five geomorphic zones which roughly parallel the present shoreline (fig. 7): (1) a hilly to mountainous system of parallel valleys and ridges (the Newer, or Folded, Appalachian Mountains), (2) a flat to hilly upland region (the Older Appalachian Mountains), (3) a coastal lowland, in places submerged below present sea-level (the Atlantic Coastal Plain and Continental Shelf), (4) a submerged slope about 1,500 fm. high (the Continental Slope), and (5) a very gently sloping surface merging seaward with the deep ocean floor (the Continental Rise). For a discussion of these geomorphic divisions see Fenneman (1938), Heezan et al. (1959), and Hammond (1964).

Before the Cretaceous Period (some 136 million years ago) a succession of evolving highlands occupied the present sites of the Older Appalachians and the Coastal Plain. According to Dietz and Holden (1966), these highlands were formed when material uplifted from an ancient Continental Slope and Rise and from the adjacent deep-sea floor was added to a then smaller continent. This process of accretion is supposed to have started in the late Ordovician Period (about 445 million years ago) and to have continued until the end of the Permian Period (about 225 million years ago), eventually adding some 150 to 400 or more miles to the continent. (Dates are from Kulp, 1961, and Harland, Smith, and Wilcock, 1964.) The eroded remnants of these old highlands now underlie Cretaceous and younger sediments on the present Coastal Plain; they outcrop in a belt of greatly deformed and altered rocks throughout the Older Appalachian Mountains.

The region west of the Older Appalachians was occupied in pre-Ordovician times by an ancient

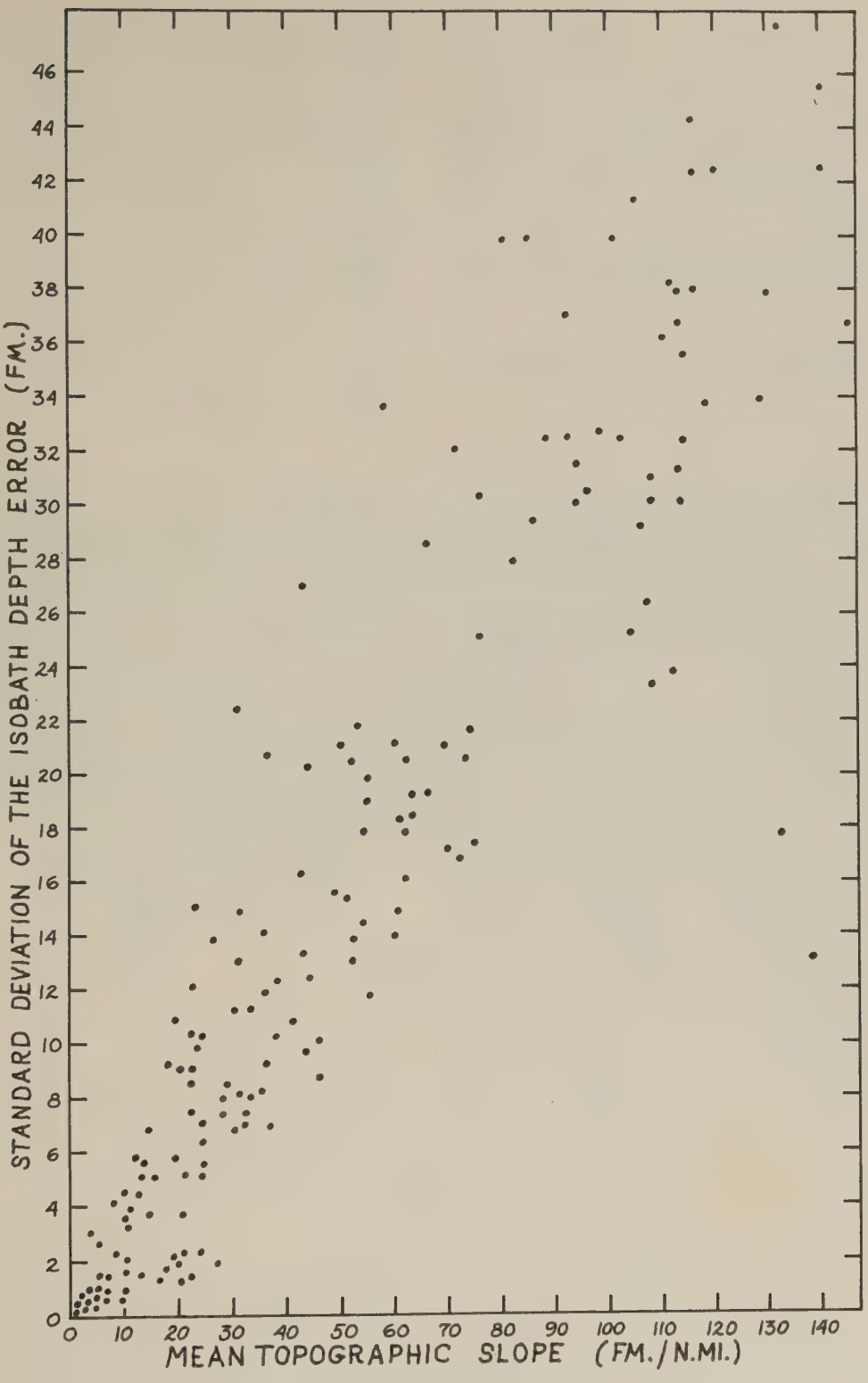

FIGURE 5.—Variation of the standard deviation of the isobath depth error with respect to the mean topographic slope.

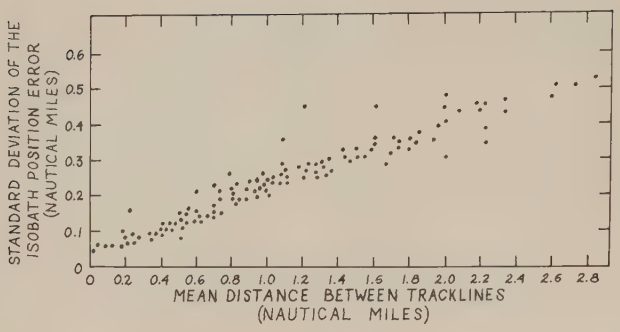

FIGURE 6.—Variation of the standard deviation of the isobath position error with respect to the mean distance between tracklines.

coastal plain and continental shelf. This plain became an epicontinental inland sea in post-Ordovician times, and its bottom was progressively folded until the Appalachian Revolution of middle and late Permian times finally forced it and its sediments into the present Folded Appalachian Mountains. The above sequence of events is only one recent inference from available evidence; for other interpretations of the geologic history of the region see Schuchert (1923), Kay (1951), Drake et al. (1959), Wilson (1966), and Harland (1967); see also the criticism by Hsu (1965) of earlier ideas of Dietz (1963a) and the reply by Dietz (1965).

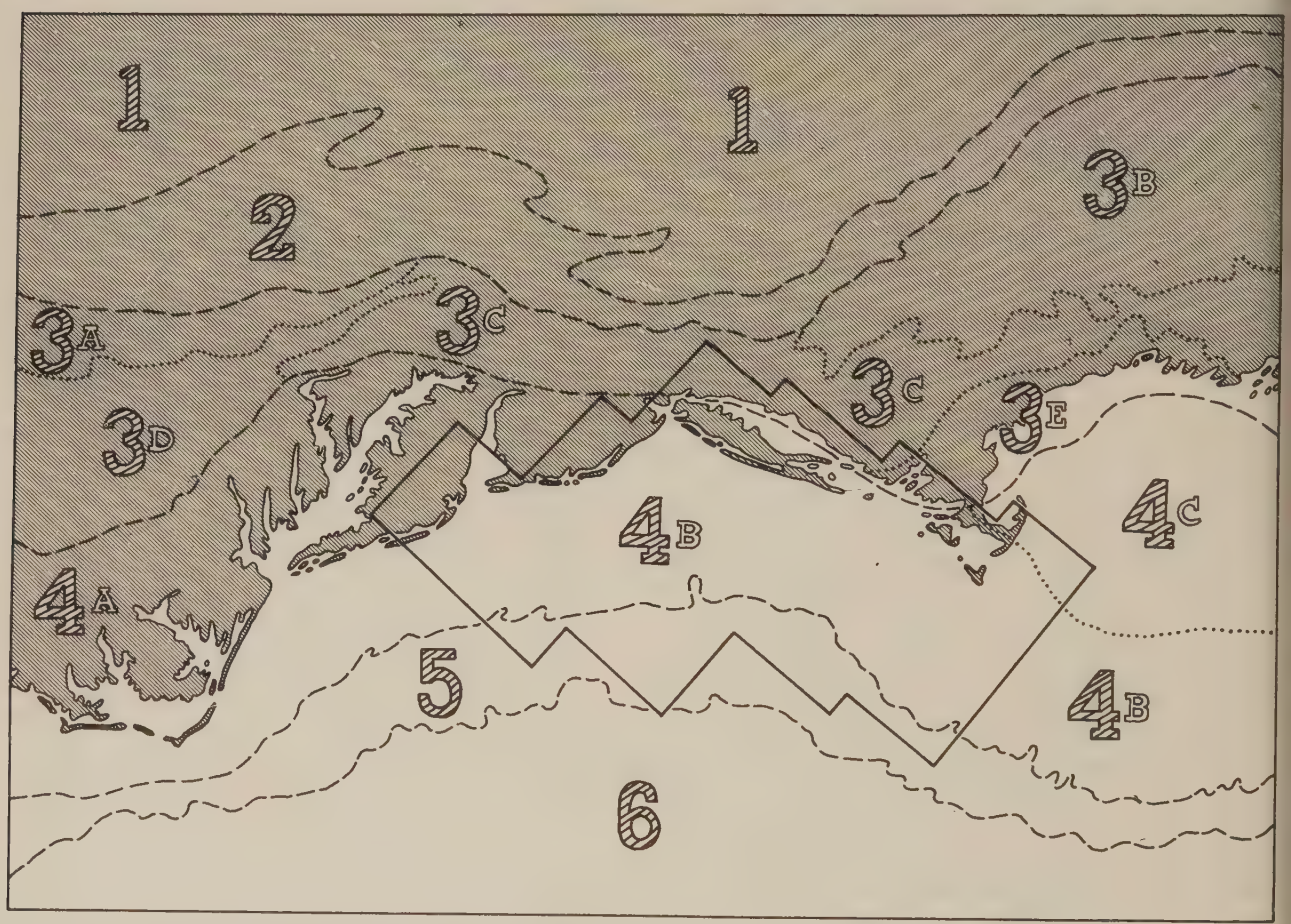

FIGURE 7.—Physiographic regions of the Middle Atlantic Coast. (1) Appalachian Plateaus and Interior Lowlands. (2) Folded Appalachian Mountains. (3) Older Appalachian Mountains, including (3A) Blue Ridge Mountains, (3B) New England-Acadian Mountains, (3C) Piedmont-New England Hills, (3D) Piedmont Plain, and (3E) New England Plain. (4) Emerged and Submerged Coastal Plain, including (4A) Emerged Coastal Plain, (4B) Submerged Coastal Plain or Continental Shelf, and (4C) Gulf of Maine Basin. (5) Continental Slope. (6) Continental Rise. Boundaries are approximate. Sources: Fenneman (1938); Heezen et al. (1959); and Hammond (1964). The heavy solid line is the boundary of the mapped area.

Since the Cretaceous Period, the eroded roots of he old coastal highlands have experienced suc-ssive invasions of the sea, and a large wedge of diment has been deposited on their surfaces. he most recent submergence was between about 000 and 20,000 years ago. (For discussions of rrestrial conditions on the shelf in the recent st see Emery, 1966a; Emery, Wigley, and Rubin, 966; and Wigley, 1966). The presently submerged rface of this sedimentary wedge is the Conti-ntal Shelf of eastern North America.

eneral Sediment Distribution

The surface of the Middle Atlantic Continental helf is covered only in part by contemporary diments. These are mainly in a narrow near-ore zone (Emery, 1961; Uchupi, 1963). The rgest part of the shelf is covered by relict de-sits formed during lower stands of sea level in he Ice Age.

Relict shelf features and sediments were recog-ized as early as 1850 by Austen who suggested hat the English Channel was once a subaerial ver valley. Dana (1863) extended Austen's idea the Middle Atlantic Continental Shelf by his iscovery on an 1852 Coast Survey chart of both he Hudson and Block submarine channels which, e concluded, were once occupied by the Hudson nd Connecticut Rivers. Taylor (1872) later sug-ested that evidence of dry land, rivers, and shore-ne features should be found within the 100-fm. ne, and during the same period Louis Agassiz ught his Harvard classes that the offshore fish-ng banks consisted superficially of glacial drift Upham, 1894). Most recent authors accept the lea of relict deposits, although emphasis shifted mewhat after Gulliver (1899) and Johnson 1919) introduced the concept of an inner shelf hich had been cut by waves and an outer shelf hich had been built up by wave deposition (for discussion of this concept see Dietz, 1963b, 1964; nd Moore and Curray, 1964).

The Middle Atlantic Shelf is covered by modi-ed glacial outwash and moraines, river channel nd flood plain deposits, ancient deltas, offshore ars, and old coastal beach-lagoon complexes Uchupi, 1968). Some smaller areas may contain aterials formed in place by submarine chemical rocesses (Uchupi, 1963; Emery, 1966b). Super-nposed on these primary sediments are patches f both contemporary and ancient shell debris (Merrill, Emery, and Rubin, 1965; Emery, Merrill, and Trumbull, 1965).

The subsurface sediments of the Shelf and Coastal Plain consist of layer after layer of much the same type of deposit that occurs today on their surface (with additions of other types such as peat and limestone). These sediments have been accumulating at least since the Cretaceous Period and now form a thick prism which ranges from a few feet at the landward border of the Coastal Plain to over 15,000 feet (4.6 km.) thick at the edge of the shelf. An even greater thickness has accumulated at the foot of the Continental Slope, and some 25,000 feet (7.6 km.) of sediments now lie under the Continental Rise (for a discussion of this deeper structure see Dietz, 1952; Drake et al., 1959; Heezen et al., 1959; Murray, 1961; Emery, 1966b; Krause, 1966; Hoskins, 1967; and Uchupi and Emery, 1967).

Geomorphic Processes

The nearshore breaking of waves is the most important cause of erosion on the landward edge of the shelf, but is apparently effective only above about 5 to 10 fm. (Dietz, 1963b; see also the discussion by Moore and Curray, 1964 and the answer by Dietz, 1964). Some controversy exists, however, concerning the ability of contemporary processes to alter significantly the relict terrains and sediments seaward of the surf-zone. Several authors have thought that present waves and currents can scour the shelf intensely to great depths (Dana, 1890; Gulliver, 1899; Johnson, 1919; Alexander, 1934; and Jones, 1941). Other workers have suggested that the present shelf surface is drowned and entirely out of adjustment with present conditions (Lindenkohl, 1891; Dietz, 1963b, 1964). Still others have believed that a thin surface layer (6–24 inches, or 15–60 cm.) is in adjustment with contemporary sea level (Donahue, Allen, and Heezen, 1966), or that fine sediments are being either moved across the shelf or deposited in certain restricted areas (Shaler, 1881; Shepard and Cohee, 1936; Stetson, 1938b; and Emery, 1966b). Uchupi (1968) suggested that some linear sand bodies on the inner shelf may have been formed by large modern storm waves. It is also possible that with a long-continued stand of the sea at its present level, the shoreline would build out over a large portion of the inner shelf (Curray, 1964; Emery, 1966b) or that existing bottom sediments

and relict land forms would eventually become completely adjusted to present sea level (Stetson, 1938b, 1939; Moore and Curray, 1964).

A distinction must be made between gross land forms and surficial sediments. All of the relict surface sediments above the late Wisconsin low stand of the sea (about 65 or 70 fm.) have been modified during the last 20,000 years or so by the active surf-zone, as this zone migrated shoreward across the shelf with the latest postglacial (or Holocene) rise of sea level. Thus, the surface sediment layer is a direct product of the Holocene marine transgression. Large terrain features, however, are not likely to have been obliterated by the Holocene rise; hence, much of the present gross morphology on the shelf is probably related to pre-Holocene events.

Between the nearshore surf-zone and the land a complex of barrier beaches, lagoons, and coastal marshes has developed along most of the Middle Atlantic Coast. This complex traps much of the sediment load now brought to the ocean by rivers and other runoff. A large volume of recent sediment is also deposited in bays or sounds, and the small amount of suspended fine material that escapes is often removed from the shelf by currents or deposited in such depressions as the Hudson and Block Channels (Stetson, 1955; Curray, 1964).

As changes have occurred in sea level, the shoreline (along with a complex of barrier beaches, lagoons, coastal marshes, and estuaries) has migrated scores of miles back and forth across what is now the shelf and the emerged coastal plain (Emery, 1967). As early as 1881 Shaler suggested that the net effect of this repeated migration, combined with a slow subsidence of the continental margin, has been the deposition of the series of layers that now form the thick sedimentary wedge of the Continental Shelf.

REGIONAL PHYSIOGRAPHY

The physiographic regions and features on the Middle Atlantic Shelf are described in terms of their topography and sediments in the following paragraphs. The major regions and features discussed are (1) nearshore terrains, (2) terrains southwest of the Hudson Channel, (3) the Hudson Channel, (4) terrains northeast and east of the Hudson Channel, and (5) terraces and ancient shore features on both the inner and outer shelf. The bathymetric maps of Stearns and Garrison (1967) serve as illustrations for this section and should be available; features mentioned in the text are keyed to these maps by chart number. The locations of some of the larger features are also shown in figure 1.

Nearshore Terrains

Nearshore terrains are easily accessible and have been much studied (see, for example, Shaler, 1893, 1895; Johnson, 1919, 1925; Shepard, 1948; and Guilcher, 1958). In the mapped area they may be divided into three types.

The surf-zone.—Parallel to the shoreline is a relatively smooth concave slope, in some places interrupted by one or more offshore bars, extending from the beach to a depth of 5 or 10 fm. The width of the surf-zone rarely exceeds 2 nautical miles (its average width is about one-half mile) and it appears to be deepest off New Jersey and eastern Long Island. The sediments of the surf-zone are mostly clean, coarse to fine sand, with a few patches of gravel and rock. Some black mud that lies between 4 and 11 fm. off New Jersey and Long Island may indicate places where the surf-zone has exposed old coastal marsh deposits such as underlie the present barrier beaches (see Fischer, 1961).

The barrier beach-lagoon complex.—Shoreward of and parallel to the surf-zone, throughout most of the mapped area, are extensive linear barrier beaches forming the seaward margin of shallow bays, lagoons, and coastal marshes. This terrain is especially well developed along the whole of the Maryland, Delaware, New Jersey, and southern Long Island Coasts. The width of the lagoon-coastal marsh terrain usually varies from 1 to 6 nautical miles. Except for tidal channels, the depth of lagoons seldom exceeds 2 fm. and is generally less than 1 fm. The marshes are at sea level, between the high- and low-tide marks; and sediments there are mud and organic plant debris. Tidal-delta sands are around inlets. Barrier beaches are clean sand often formed into sand dunes by the wind (see Lucke, 1934a, 1934b; and Fischer, 1961).

Glacial moraines.—Running across the northern part of the mapped area is a zone of low hills separated from the southern New England shore by a series of bays and sounds. This region of old glacial moraines forms numerous submerged features as well as the backbones of Long Island,

lock Island, and the islands south of Massachutts (Schafer and Hartshorn, 1965). Long Island as two moraines: the Harbor Hill Moraine exnds along the north shore to Orient Point and nen across Long Island Sound through Plum, reat Gull, and Fishers Islands to Watch Hill oint in Rhode Island and along the shore (where is called the Charlestown Moraine) to Point udith; the Ronkonkoma Moraine runs through entral Long Island to Montauk Point. These two oraines are considered to have formed during the st advance of the late Wisconsin ice-sheet some 0,000 years ago (Flint, 1957; and Donner, 1964). hey merge to the west, south of Hempstead Harbr, and continue across Brooklyn to Staten Island nd New Jersey.

Where the Harbor Hill Moraine crosses Long sland Sound there is a ridge of coarse rocky sediients (chart 0808N–53 of Stearns and Garrison, 967). Between the high points on this ridge are ongated depressions and channels, some as deep s 55 fm., containing finer sediments. Some of nese depressions may be kettles formed by the elting of buried blocks of ice (Elliott et al., 955), or they may have been cut by either iceour or subglacial drainage streams (Dana, 1870, 875, 1883, 1890; Loring and Nota, 1966, suggested nis origin for similar features in the Gulf of St. awrence). These pre-Holocene depressions would ave become fresh-water lakes shortly after being ncovered by the melting ice-sheet (Antevs, 1922, 928; Lougee, 1953); evidence for these lakes, in ne form of fresh-water clay concretions, has been und in one depression south of Fishers Island Frankel and Thomas, 1966). Some other depresons may have been formed or at least modified, river erosion, during the period which followed ne retreat of the ice-sheet. All the depressions robably have been scoured by tidal currents which ecame effective in this area when the sea had isen to 10 to 15 fm. below present sea level.

The Ronkonkoma Moraine extends beyond Long sland, from Montauk Point to Block Island, and s crossing is marked by a broad ridge of coarse ocky and bouldery sediments (charts 0808N–51 nd –53). Near its center this band is breached by channel, which contains several 25- and 30-fm. oles. This breach probably represents one of the ncient channels for the rivers of Connecticut and western Rhode Island. It was later eroded by tidal currents when sea level rose to within 10 or 15 fm. of its present level.

East of Point Judith, R.I., the Harbor Hill (or Charlestown) Moraine appears to bend southward around Narragansett Bay and to join with the Buzzards Bay Moraine of western Cape Cod by way of Browns Ledge and the Elizabeth Islands (chart 0808N–51). This bend is marked by a submerged ridge of coarse gravelly sediments. East of Block Island the Ronkonkoma Moraine also appears to bend to the south and to join with moraines on the north shores of Martha's Vineyard and Nantucket Island by way of Nomans Land, the Southwest Shoal, and Cox Ledge. The bottom in this area is marked by a broad rocky and gravelly ridge (Schafer, 1961; and Kaye, 1964).

Between Block Island and Martha's Vineyard this ridge is breached by a channel with depths as great as 35 fm. The sea bottom between the two moraines in this area contains an east-west channel with depths that approach 30 fm. to the north of Block Island. This east-west channel continues westward through Block Island Sound and eastward as far as the entrance to Vineyard Sound. This channel probably represents an early Holocene drainage system for much of southern New England. Presumably, late Holocene drainage from Connecticut broke through the moraine east of Montauk Point, while Rhode Island and Massachusetts drainage continued down the channel east of Block Island. It appears that both these systems entered the Block Channel across the shelf. The channels have been modified by tidal scour and tidal delta deposition which would have started when the sea rose to about 25 fm. below present sea level.

The moraines on Martha's Vineyard, Nantucket Island, and Cape Cod cannot be traced to the east with certainty (see chart 0708N–51). They probably merge with the lateral moraine of an ice-sheet lobe that once extended southward through the Great South Channel (see Zeigler, Tuttle, Tasha, and Giese, 1964). Between Martha's Vineyard and Nantucket Island is a double tidal delta which appears to have been built in an old tributary of the Block Channel that once ran between the Islands.

Terrains Southwest of the Hudson Channel

Off the coasts of New Jersey, Delaware, and Maryland, the bottom above about 50 fm. consists of alternate ridges and longitudinal depressions, which generally run northeast-southwest and are interspaced by flat areas, escarpments, embayments, and former channels. The sediments on this part of the shelf are predominantly sands with some coarser material. Muds are infrequent above about 50 fm. and are not dominant shallower than the shelf break.

The terrains in this area are similar to present nearshore and modified subaerial alluvial terrains; this similarity is not surprising because the surf-zone, the complex of lagoons and coastal marshes, and the subaerial river regimes must have repeatedly migrated back and forth across the shelf. Flint (1940) noted that north of the James River the Pleistocene formations on the emerged coastal plain are typical of compound alluvial deposits. It seems that this is also true of the submerged shelf, with the addition of numerous transgressive marine features (see also MacClintock, 1943, and Schlee, 1964).

Delaware River channels.—From the mouth of Delaware Bay a channel may be traced southeastward about 40 nautical miles (Lindenkohl, 1891; charts 0807N–56 and –57). Below 20 fm. this channel is lost in a series of what appear to be old lagoons and barrier beaches which continue down to about 40 fm. To the northeast the channel is bounded by a scarp as much as 15 fm. high. A well-defined ridge backing this scarp can be traced 30 nautical miles southeastward from Cape May, and its remnants extend for another 30 or 40 nautical miles.

Northeast of this ridge is a shallow embayment that has a diffuse channel below 5 to 7 fm. (charts 0807N–55 and –56). Deeper than 20 fm. this embayment flattens out and merges with what appears to be a series of lagoons and barrier beaches. Possibly this bay represents an older Delaware River estuary which might be correlated with a post-Sangamon channel in the Cape May Formation on the Cape May Peninsula (Richards, 1962).

Great Egg Harbor River channel.—Running southeast from near Great Egg Harbor Inlet is a smooth embayment that extends to a depth of 12 or 14 fm., where a bar has been built across its mouth (chart 0807N–55). Beyond this bar the bay narrows and a shallow channel continues south-southeastward. Between 18 and 22 fm. a ridge, about 20 nautical miles long, appears to have been a large barrier beach. It encloses what was probably a former lagoon, now as much as 2 or 3 fm. deeper than the surrounding bottom. Below this feature, the channel is lost in a deeper series of what seem to be lagoons and barrier beaches. The northeast boundary of the embayment off Great Egg Harbor Inlet is a low ridge extending southeasterly from Brigantine Shoal; it appears to be composed of a series of submerged sand spits and barrier beaches.

The old and new Delaware embayments and the Great Egg Harbor embayment are each well defined between about 10 and 20 fm. Below about 20 fm., however, the new Delaware embayment is lost, and the old Delaware and Great Egg Harbor embayments are combined, first into a large shallow depression (about 35 nautical miles long) between 24 and 27 fm. and then into a single open embayment between 27 and 29 fm. (charts 0807N–55 and –56). Below about 28 fm., this open embayment narrows into a slender channel which continues southward to about 35 fm., where it is lost in what may be a complex of former lagoons.

The Shelf northeast of Brigantine Shoal.—Northeast of Brigantine Shoal the shelf is dominated by several large northeastward trending embayments, and by two north-south trending channels, which are associated with a submerged alluvial gravel deposit (Schlee, 1964; charts 0807N–54 and –55). One of the north-south trending channels heads offshore near lat. 39°45′ N. and may be traced southward for about 30 nautical miles, roughly along long. 73°50′ W.

West of this channel is a very smooth and flat plain, whose shallow limit is defined by the 10- or 11-fm. isobath. On the east it is bounded by a low scarp and backed by a north-south ridge with a minimum depth of less than 9 fm. This ridge is distinct for at least 35 nautical miles along the bottom, and remnants of it extend even farther both north and south.

East of this ridge is the second of the north-south channels mentioned above. It originates near lat. 39°50′ N. and runs southward for about 30 nautical miles between long. 73°28′ and 73°33′ W. This channel is defined by the 19- to 21-fm. iso-

aths and is extensively barred throughout its ength at those depths.

West of this second channel is another plain, omewhat dissected by northeasterly trending de- ressions; to the east is a broad flat-topped ridge ith minimum depths of between 17 and 18 fm. Most of the channels on the east side of this ridge rend northeastward toward the Hudson Channel. North of lat. 39°50′ N., all of the old shelf chan- els run eastward or northeastward toward the Hudson Channel.

The gravel deposits near these north-south chan- els seem to have added about 5 fm. to the shelf urface off the coast of northern New Jersey. When ompared to the surface south of Long Island this uildup is shown by a greater offshore extent of he 20- to 30-fm. isobaths (compare charts 0807N–4 and 0808N–54 and –55). According to Schlee (1964), these deposits are at least 10,000 years old nd were probably deposited by the ancestral Hud- on River.

The northernmost and largest of the northeast- ard trending embayments runs roughly along a ne between lat. 39°05′ N., long. 74°04′ W. and t. 39°24′ N., long. 73°20′ W. (chart 0807N–55). t is well defined between about 20 and 25 fm. and ccurs immediately below the submerged gravel eposit described by Schlee (1964). It can be traced or some 50 nautical miles across the shelf and ap- arently connects with the 37- to 38-fm. depression elow Tiger Scarp (chart 0807N–52). Southeast f this largest embayment are four similar but naller embayments. All of these embayments are ounded on their northwest sides by low scarps nd all lead into a north-northeast trending series f apparent lagoons and channels below about 5 fm. To the south these embayments are defined y the 24- to 26-fm. isobaths, but they are progres- vely less well formed as the end of the Brigantine hoal Ridge is approached.

he Hudson Channel

The Hudson Channel is the best defined of the ld river valleys on the shelf. It was first discov- ed during the 1842–44 surveys and originally apped as a series of discrete "mud holes." Dana (1863) later suggested that these holes were part f a continuous valley that had been eroded by he Hudson River. The survey of 1882 demon- rated the continuity of the channel.

The Hudson Channel extends some 85 nautical miles across the shelf from off the entrance to New York Harbor to the head of the Hudson Canyon (charts 0807N–52 and –54, and 0808N–55). It is very shallow at its upper end, but some 10 nautical miles southeast of Sandy Hook it deepens abruptly, runs about 15 nautical miles southward, and then turns southeastward across the shelf. It is divided into a series of basins which are floored with mud and muddy sand. It becomes partially lost in an elongated flood plain and delta below about 40 fm., but several buried channels have been traced through this area, the youngest of which connects to the present head of the Hudson Canyon (Ewing, LePichon, and Ewing, 1963).

According to Ewing et al. (1963), the present Hudson Channel and Delta and the upper slope portion of the Hudson Canyon have all been in much the same position throughout the late Pleistocene. Very likely, however, the present head of the canyon is only one of the latest feeder channels for the lower canyon. Ewing et al. (1963) showed some old buried discontinuities (possibly erosion surfaces) which head northeast of the present canyon. Robertson (1964) suggested that the Georges Bank canyons were eroded during a Pliocene emergence, filled during an upper Pliocene or very early Pleistocene submergence, and then re-excavated during the Pleistocene. Some of the canyons which are immediately northeast of the Hudson Canyon, and which have their present heads below 100 fm. may be of Pliocene age and have not had their heads re-excavated because the Hudson drainage moved out of the area.

Terrains Between the Hudson Channel and the Block Channel

The shelf surface south of Long Island (charts 0808N–53, –54, and –55) has at least three types of relict terrains. Between about 15 and 35 fm. it is characterized by low ridges and shallow channels and appears to be a stream-dissected alluvial plain modified by minor features formed during the Holocene transgression. It is not covered by extensive late Pleistocene alluvial gravels like the shelf southwest of the Hudson Channel.

The shelf surface above about 15 fm. is dominated by Wisconsin glacial outwash and appears as a sand plain in front of the old moraines on Long Island. It has been much modified by early Holocene stream erosion, the late Holocene marine transgression, the modern surf-zone, and possibly

by present-day storm wave action (see discussions of this region by Dana, 1875; Lindenkohl, 1885, 1891; Shepard and Cohee, 1936; Stetson, 1938b, 1949; Lougee, 1953; Elliott et al., 1955; Garrison and McMaster, 1966; and Uchupi, 1968). Below about 35 fm. the surface appears to be dominated by deltaic and alluvial deposition rather than by erosion.

As Garrison and McMaster (1966) pointed out, two major directions of past drainage are apparent on the present shelf surface south of Long Island; one (north of about lat. 40°20′ N.) is eastward into Block Channel, and the other east and southeastward into a large embayment (well defined between about 40 and 45 fm. on charts 0807N–52 and 0808N–54) near lat. 40°00′ N. and long. 72°10–15′ W.

The Block Channel

The Block Channel was discovered during the same surveys of 1842–44 that found the Hudson Channel. This broad and shallow channel extends some 70 nautical miles across the shelf, from inside Block Island Sound to its delta at the shelf break (charts 0807N–51, and 0808N–51 and –52). Block Channel has several minor tributaries entering from the west and two major tributaries entering from the east—one from Rhode Island Sound and Buzzards Bay, and the other from the area south of Nantucket Sound. The Channel and its Rhode Island Sound tributary contain what are apparently well-developed tidal deltas between about 23 and 26 fm.

Dana (1863) suggested that the Block Channel had been eroded by the Connecticut River. Garrison and McMaster (1966) considered it to have been the main trunk for southern New England drainage during late Wisconsin and Holocene times, and Krause (1966) suggested that its delta was forming throughout the Pleistocene. These authors noted that the delta's present form was reached during the early Holocene when sea level was about 45 fm. below the present one. This level is similar to the depth of formation of about 43 fm. proposed by Veatch and Smith (1939) for the Hudson Delta.

Surficial sediments in the Block Channel consist of about 16 inches (41 cm.) of fine fluvial and estuarine sands and silt, probably of Holocene age. These overlie clean medium sands of Wisconsin age and of fluvial origin. The upper 1 inch (2 cm.) or so is sandy silt, with a very high water content; it is probably late Holocene or modern sediment (McMaster and Garrison, 1966; Garrison and McMaster, 1966).

Terrains Between the Block Channel and the Great South Channel

The sea floor east of the Block Channel (exclusive of Nantucket Shoals) is zoned much the same as to the west, although it is very much smoother, contains fewer stream channels and other well-defined offshore features, and is partly covered by considerably different sediments (charts 0807N–51, and 0808N–51 and –52).

Above about 20 fm. the bottom is rough and is composed of Wisconsin glacial outwash and morainal deposits modified by stream erosion, by the late Holocene transgression, and by the present surf-zone. Between about 20 and 35 fm. the shelf is of very low relief and appears to be an alluvial plain modified by a few transgressive features.

The surficial sediments on this plain are fine to coarse sands, which Garrison and McMaster (1966) considered to be pre-Holocene fluvial deposits later reworked by the Holocene transgression. To the east, around the margin of Nantucket Shoals, these authors believed these fluvial sands to be covered by fine sand derived from the Shoals during the late Holocene or present.

The silty region south of Martha's Vineyard.—Below about 30 to 35 fm. evidence of stream erosion is sparse, the bottom is very smooth, and the surface sediments change to sandy silt (chart 0808N–52). This region is unique because it is the only extensive muddy deposit on the entire East Coast Continental Shelf that is not associated with a marked depression. It was first mentioned by Pourtales (1870).

Lindenkohl (1885) considered this muddy area to be a region of Tertiary outcrop that had not been covered by Pleistocene deposits. Shepard and Cohee (1936) thought that the silt was a modern deposit derived from Georges Bank. Stetson (1938b) also thought that silt was now being added to older sand deposits in the area, and Chamberlin and Stearns (1963) have suggested a current eddy to account for this deposition. Garrison and McMaster (1966) noted that the northern edge of the silt deposit is strongly intermixed with older alluvial sands and that the eastern edge appears to

e overlain by younger sand derived from Nan-
ucket Shoals. They believed that the silt accumu-
ated in a topographic depression during the Holo-
ene rise of sea level. Furthermore, they suggested
lt beds under Nantucket Shoals as the source and
laced the age as late Holocene (after the sea had
sen to about 35 fm. below present sea level) be-
ause the surface appears smooth and uneroded.

The smooth appearance in this area may be a
ata artifact, resulting from a rather wide spacing
f survey tracklines. Just to the east of the Block
)elta is a small well-surveyed area (USCGS Hy-
rographic Survey No. 6659) that shows the bot-
m finely dissected by many small channels and
overed with a few small mounds and depressions.
lthough this survey may indicate what the sur-
ounding region would look like if surveyed in
omparable detail, there is some doubt that it does.[2]
he average standard deviation of the isobath posi-
on error in the area of USCGS Hydrographic
urvey No. 6659 is 0.13 nautical mile and, because
ne principal tracklines run parallel to the trend
f the small channels (i.e., up and down slope),
ngthwise line shifts of one or two times this
mount would account for much of the fine detail
hown. Some of the crosslines run in this survey,
owever, give evidence of shallow channels, and it
eems probable that the true appearance of the
ottom lies somewhere between the two extremes
ndicated.

Nantucket Shoals.—For a distance of 30 to 50
autical miles to the south and southeast of Nan-
ucket Island is a vast expanse of sand shoals and
tangle of many smaller ridges and depressions
charts 0708N–51 and –52). Collectively, this area
s called Nantucket Shoals and has been known
ince the earliest explorations of the east coast (see
ich, 1929). Two old maps showing Nantucket
hoals, one made about 1656 and the other about
730, are reproduced in Gottmann (1961).

From geologic mapping of Nantucket Island,
Martha's Vineyard, and Cape Cod, it appears that
Nantucket Shoals are relict glacial deposits laid
own when the sea was 25 fm. below its present
evel. The large shoals abutting on the Great South
Channel contain a few patches of gravel and prob-
bly constitute a much modified glacial moraine
ormed by a late Wisconsin ice-lobe in that chan-
nel. Farther to the west, Nantucket Shoals prob-
ably were derived by reworking outwash from the
west side of this South Channel moraine, or from
an interlobate outwash deposit formed between the
South Channel ice-lobe and another ice-lobe ex-
tending through Cape Cod Bay (Zeigler et al.,
1964, suggested that outer Cape Cod is an inter-
lobate deposit formed between these two lobes),
or from end moraines of the Cape Cod Bay ice-
lobe. Whatever their exact source, these Shoals
have been much altered by early Holocene stream
erosion and by late Holocene and modern tidal cur-
rent and surf-zone action (Lindenkohl, 1883;
Curtis, 1913).

Old silt beds occur under the Shoals, and Living-
stone (1964) considered them to be of Sangamon
age. (Athearn (1957) came to the same conclusion
for a similar silt layer about 43 fm. below sea level
some 60 nautical miles south of Moriches Bay,
Long Island.) Groot and Groot (1964) found that
samples of the upper 5 feet (1.5 m.) of the silt
near Fishing Rip contained a mixture of Creta-
ceous, Tertiary, and Pleistocene pollen and spores,
as well as a marine shell about 11,500 years old.
It, thus, seems that the silt layer, at least near
Fishing Rip, has been covered by the Shoal sands
only in the late Holocene—probably by material
washed southwestward from the lateral moraine
of the South Channel ice-lobe. This type of win-
nowing has been invoked by Garrison and Mc-
Master (1966) to account for the band of fine sand
covering the silty area to the west of Nantucket
Shoals (see also Shaler, 1893). Uchupi (1968) sug-
gested, however, that some of this sand may have
come from the erosion of the outer arm of Cape
Cod.

The Great South Channel.—The existence of the
Great South Channel was inferred from local sur-
face currents by Captain John Smith as early as
1614 (Rich, 1929). It separates Georges Bank from
Nantucket Shoals and is a broad and flat but
rough-bottomed valley with a sill at about 40 fm.
(lat. 40°36′ N. on chart 0708N–52). It is divided
into a number of shallow basins by low sills. This
Channel was probably occupied by a lobe of the
late-Wisconsin ice-sheet, from which outwash and
moraines contributed to both Little Georges Shoal
to the east and Nantucket Shoals to the west (see
Zeigler et al., 1964). In pre-Pleistocene time Great
South Channel may have been a stream valley

[2] Personal communication from John S. Schlee, U.S. Geo-
gical Survey, Washington, D.C.

(Johnson and Stolfus, 1924; Shepard, Trefethen, and Cohee, 1934; Emery and Uchupi, 1965; and Uchupi, 1966a, 1966b).

Terraces and Shore Features on the Outer Shelf

Below about 40 fm. the outer shelf is characterized by (1) an alternation of discontinuous scarps and relatively flat terraces, some with superimposed linear ridges of coarse sands and gravels (especially well developed off New Jersey and Delaware) and (2) by ancient river deltas (especially south of New England). Most authors describe the scarps and terraces as old shoreline features, developed during lower Pleistocene sea levels (Taylor, 1872; Newberry, 1878; Lindenkohl, 1891; Shepard, 1932; Stetson, 1938b; Veatch and Smith, 1939; Dietz, 1952; and Emery, 1961).

Old shore lines.—Three sets of terraces with bars and spits are observable throughout the area. The deepest set is between 82 and 90 fm. and averages about 85 fm. Remnants of this set may be seen between Veatch Canyon and Atlantis Canyon (86–90 fm. on chart 0708N–53), just to the east of the head of Block Canyon (82–84 fm. on chart 0807N–51), and to the northeast of Hudson Canyon (82–86 fm. on chart 0807N–52). In addition, Ewing et al. (1963) discovered an 80- to 90-fm. buried erosion surface near the Hudson Canyon (their 165-m. terrace).

A shallower set, from 73 to 81 fm. and averaging about 77 fm., may be seen between Veatch Canyon and Atlantis Canyon (a double set at 78–81 and 73–76 fm. on chart 0708N–53), and to the northeast of Toms Canyon (73–78 fm. on chart 0807N–53). The 85- and 77-fm. sets of terraces south of New England have been combined by Garrison and McMaster (1966) into what they call the 80-fm. terrace.

These terraces are backed by a discontinuous scarp, whose foot is at an average depth of about 77 fm.; this scarp is the Nicholls Shore of Veatch and Smith (1939). It is well defined in the subsurface (Ewing et al., 1963) and, for the most part, appears to be a constructional escarpment formed by younger sediments deposited on an older surface. A more poorly developed deeper scarp, with its foot at about 86 fm., can be seen between Veatch Canyon and Atlantis Canyon (chart 0708N–53), and just to the west of Atlantis Canyon where it merges with the higher Nicholls Shore (chart 0807N–51).

The next set of terraces is between 56 and 71 fm. and averages about 64 fm.; it may be seen between Hydrographer Canyon and Veatch Canyon (59–62 fm. on chart 0708N–53), as well as to the west of Atlantis Canyon (64–70 fm. on chart 0807N–51), and to the northeast of Hudson Canyon (59–62 and 62–70 fm. on chart 0807N–52), Toms Canyon (64–71 fm. on charts 0807N–52 and –53), Wilmington Canyon (56–59 and 63–65 fm. on chart 0807N–56), and Baltimore Canyon (62–66 fm. on chart 0807N–56). Referring to the region south of New England, Garrison and McMaster (1966) called this set the 65-fm. terrace. It is backed by a poorly developed scarp whose foot is at an average depth of about 64 fm. Called the Franklin Shore by Veatch and Smith (1939), this scarp appears to be partly constructional and partly destructional in origin. Ewing et al. (1963) could not find a clear subsurface indication of the Franklin Shore near the Hudson Canyon.

Although these three sets of terraces and scarps were certainly formed when the sea was at various lower levels than at present, it is not easy to determine the exact levels. The difficulty was made plain by Johnson (1910, 1932), Johnson and Winter (1927), and Miller (1939) in discussions of the problems involved in correlating old shorelines now above sea level. These authors concluded that at a given sea-level shoreline features can be developed at different elevations and that determination of former sea levels by physiographic methods alone is, consequently, very inaccurate. Johnson (1932) has also pointed out that a distinction must be made between the elevations of erosional and depositional features formed at the same sea level. All of these conclusions are also applicable to submerged features

Numerous estimates of former sea levels on the outer shelf have been based on appraisals of the eustatic lowering of sea level during the formation of the Pleistocene ice-sheets (e.g., Maclaren, 1842; Taylor, 1872; Shaler, 1875; Daly, 1925; Fairbridge, 1960; Curray, 1961; and Shepard, 1961). Donn, Farrand, and Ewing (1962) give double estimates for this eustatic lowering which correspond with two different estimates of the present thickness of the Antarctic ice-cap. These, combined with dates taken from Emiliani (1961, 1964, 1966) and

Broecker (1966), are: (1) a maximum Illinoian lowering of about 75 or 88 fm. (some 110,000 years ago), (2) a maximum early Wisconsin lowering of about 63 or 74 fm. (some 53,000–60,000 years ago), and (3) a maximum late Wisconsin lowering of about 58 or 68 fm. (some 18,000–20,000 years ago).

In addition to these three terraces, Garrison and McMaster (1966) have noted the existence of another terrace formed when sea level stood at about 45 fm. This level seems to have been the latest episode in (1) large delta formation, especially south of New England, and (2) extensive barrier beach-lagoon formation off New Jersey and Delaware. The 45-fm. terrace is well developed near the Block Delta, where there is also evidence of small lagoons to the east (chart 0808N–52), and of a large spit and a barrier beach-lagoon complex to the west (charts 0807N–51 and 0808N–54). The terrace is also well developed between the Block Delta and the Hudson Canyon (chart 0807N–52) and between Toms and Wilmington Canyons where a large embayment and an extensive series of barrier beaches and lagoons seem to have formed (chart 0807N–53).

Deltas.—Old river deltas along the 45-fm. terrace are especially well developed northeast of the Hudson Channel. The 45-fm. level was the most recent episode in a long history of large-scale deltaic deposition on this part of the outer shelf. The most typical and best preserved of the old deltas is associated with Block Channel (Garrison and McMaster, 1966). From seismic profiles Krause (1966) has concluded that this delta probably existed throughout the Pleistocene. Where it bulges out over the edge of the shelf and onto the upper Continental Slope, Krause's profiles revealed a large area of bottomset beds.

Between the Block and Hudson Deltas a small delta is associated with the southeasterly drainage pattern south of Long Island. Probably of late Wisconsin or Holocene age, this delta appears to lie almost completely above the 64-fm. terrace northeast of the Hudson Canyon (chart 0807N–52).

The Hudson Channel disappears below about 40 fm. in what Veatch and Smith (1939) have called the Hudson Apron, a large delta whose latest stage of construction occurred when sea level stood at about 43 fm. The large bar, or spit, just to the northeast of the Hudson Canyon, may represent the remains of an earlier delta built during or shortly after the late Wisconsin maximum sea level regression (which probably formed the 64-fm. surface under this feature). Similar large spits to the northeast of both Wilmington and Baltimore Canyons (chart 0807N–56) may also be remnants of early or late Wisconsin deltas—probably built in this area by the Delaware River. Little evidence exists of delta formation at the 45-fm. level east of Block Channel.

Canyons and the slope complex.—The Continental Slope of Eastern North America was discovered in the early 19th century, but it was not studied in detail until the 1870's, when the first successful wire-sounding machines were introduced. The Coast Survey steamer *Blake* surveyed the slope during 1877–80 (Agassiz, 1888), and the Fish Commission steamers *Fish Hawk* and *Albatross* did extensive deep-water biological dredging, especially south of New England, during the 1880's.

Although the upper parts of canyons on the edge of the Scotian Shelf and Grand Banks had long been known to commercial fishermen (see Collins, 1885, and Johnson, 1885), no evidence of Middle Atlantic canyons was obtained until the 1842 work of the Coast Survey. After the soundings from the 1842 surveys were plotted, nautical charts carried notations of a "145-fathom hole" near the head of Hudson Canyon. Dana (1863) used an 1852 chart to trace the Hudson and Block Channels across the Shelf, but the new surveys of 1882 were required to show the immense size of the Hudson Canyon and its extension to the bottom of the Continental Slope (Lindenkohl, 1885). The upper part of another canyon, later named the Atlantis Canyon, was discovered by the *Albatross* in 1884 (Tanner, 1886). After the discoveries of the 1880's the canyons were much discussed (see Upham 1890a, 1890b, 1894; and Spencer, 1890, 1903, 1905a, 1905b)—usually in attempts to support theories of a vast uplift of the North American continent during the late Tertiary or early Pleistocene, which was supposed to have caused the ice age—but little new field work was done until the surveys by the USCGS in the 1930's (discussed by Shepard, 1931, 1933a, 1933b, 1934, 1938; Daly, 1936; Shepard and Beard, 1938; and Stetson, 1938a, 1938c). This work culminated in the report and charts of Veatch and

Smith (1939)—see also Smith (1939, 1940a, 1940b, 1941).

The origin of these canyons is still an open question, but most recent authors believe that they were formed by a combination of fluvial processes delivering sediment during lower stands of the sea and submarine transport of the sediment by mass movement and turbidity currents seaward of the shelf. Review articles on the canyons as well as on the Continental Slope and Rise have been made by Johnson (1938–1939, 1939), Veatch and Smith (1939), Stetson (1949), Deitz and Menard (1951), Dietz (1952, 1963a), Kuenen (1953), Drake et al. (1959), Heezen et al. (1959), Shepard (1963), Guilcher (1963a, 1963b), Heezen (1963), Moore and Curray (1963), Hoskins and Hersey (1965), Emery (1966b), Krause (1966), and Heezen, Hollister, and Ruddiman (1966).

The surface sediments of the slope and canyons consist of rock outcrops, deltaic deposits, and slumping debris, all of which are more or less covered by a veneer of late Pleistocene and present-day muds and organic oozes.

Terraces and Shore Features on the Inner Shelf

For the most part the inner shelf is made up of alluvial plains that have been modified by glacial outwash and by the Holocene transgression. Much of this has been discussed in preceding sections, but some of the better defined features deserve further mention. Although transgressive features occur on the inner shelf at almost every level between the present shore and about 40 fm., they seem to be concentrated in at least four major bands that occur at about 6 to 15, 15 to 27, 28 to 33, and 33 to 40 fm.

The shallowest of these bands (6–15 fm.) has been described by McMaster and Garrison (1967) who noted evidence of a barrier spit and lagoon south of Block Island at about 13 fm. (chart 0808N–51). Similar spits can also be found at about 13 fm. southeast of Cape May (chart 0807N–56), across the Great Egg Harbor River Channel and east of Brigantine Shoal (chart 0807N–55), southeast of Montauk Point (chart 0808N–53), east of Point Judith and south of Nomans Land (chart 0808N–51). Furthermore, Elliott et al. (1955) have noted a ridge, which crosses the Delaware Channel at a depth of about 15 fm., and have suggested that this ridge may be the remains of a submerged coastal terrace (chart 0807N–57).

The 6- to 15-fm. band is also well represented by channel bars and small depressions off the coasts of Delaware and New Jersey, by the barred terrace below Cholera Bank south of western Long Island (chart 0808N–55), by the tidal delta between Martha's Vineyard and Nantucket Island (chart 0808N–51), and by the higher parts of Nantucket Shoals. Most of these features are probably of late Holocene age.

The second band (15–27 fm.) is represented by: many apparent channel bars, barrier beaches, and lagoons off the coasts of Delaware and southern New Jersey; by spits and bars above Tiger Scarp (chart 0807N–52); by Cox Ledge south of Narragansett Bay and the tidal deltas in the Block Channel system (chart 0808N–51); and by a platform with numerous sand ridges south of the southeastern part of Nantucket Shoals (chart 0708N–52). These features are probably of Holocene age, with the possible exception of the platform south of Nantucket Shoals. This platform may represent the old silt beds under the Shoals and may be as old as the Sangamon (Livingstone, 1964); however, its covering of sand ridges is probably Holocene (Groot and Groot, 1964).

A Holocene age estimate for the features in this band is supported by the discovery of fossil oysters, *Crassostrea virginica*, some with radiocarbon ages of 7,300 to 10,300 years, at depths of 18 to 24 fm. throughout the mapped area (Merrill et al., 1965; Emery and Garrison, 1967). Living oysters of this species are found almost entirely in shallow inshore waters. Old fresh-water peat deposits, with radiocarbon ages of 8,600 to 11,000 years, have also been found in this band on Nantucket Shoals (Emery, Wigley, Bartlett, Rubin, and Barghoorn, 1967).

The third band (28–33 fm.) is represented by bars and lagoons off southern New Jersey and by barred terraces south of Long Island and Massachusetts. These features are also probably of Holocene age. Fossil oysters, some with radiocarbon ages of 9,800 to 10,800 years, have been found concentrated in this band throughout the area (Merrill et al., 1965; Emery and Garrison, 1967). An old peat deposit has been found at a depth of about 32 fm. on Georges Bank, just to the east of the region discussed in the present report; this has a

adiocarbon age of about 11,000 years (Emery et l., 1966, 1967).

The fourth band (33–40 fm.) is marked by everal terrace remnants, some with extensive bars nd lagoons. For example, the foot of Fortune carp (northeast of the Hudson Delta) lies at bout 37 to 38 fm. and the foot of Tiger Scarp at bout 33 to 36 fm. (chart 0807N–52). Garrison nd McMaster (1966) also noted that a significant ercentage of what appear to be Holocene ridge ops south of New England are at depths of 34 to 9 fm. and an old fresh-water peat deposit has een discovered at 36 fm. just south of the mapped egion (Emery et al., 1967). This peat has a radio-arbon age of 13,500 years.

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'EEDING RATES OF STARFISH, *ASTERIAS FORBESI* (DESOR), AT CONTROLLED WATER TEMPERATURES AND DURING DIFFERENT SEASONS OF THE YEAR

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ABSTRACT

Starfish were held for 28 days in pans with running a water maintained at a series of constant temperatures, with oysters as food. The average number of ysters eaten per starfish during this period was 2.3 at C., 3.0 at 10° C., 4.1 at 15° C., 5.0 at 20° C., 2.8 at .5° C., and 1.0 at 25° C. Starfish lost weight at 25° C. o observe seasonal feeding rates, starfish and oysters ere held in trays suspended in Milford Harbor, Conn. tarfish fed little from mid-January to the end of arch, but the rate of feeding then increased rapidly to a maximum in late June and early July. After mid-July, starfish fed at about one-third the rate of late June. This second period of low feeding, which appeared to be associated with both high temperatures and spawning, lasted from July through September. From late October through early December the rate of feeding increased again to about two-thirds of the level in late June and early July, before decreasing again to the seasonal low in mid-January.

Information in the literature on feeding rates of arfish, *Asterias forbesi* (Desor), is limited, and o one has reported studies of feeding rates at different specific temperatures maintained within osely controlled limits. In addition, no one has reorted quantitative studies that describe possible anges in feeding rates during different seasons of e year. Although Galtsoff and Loosanoff (1939) ated that starfish in Long Island Sound feed ore actively during the summer than during the inter, they did not determine specific rates. eedler (1941) reported that *Asterias vulgaris* Verrill) in waters of Eastern Canada feed mostly the spring and fall and relatively little in the inter. (In both Long Island Sound and Eastern anada, water temperatures fall to slightly below C. in the winter.) According to Hancock (1955, 958), *Asterias rubens L.*, which inhabit English aters, feed at a high rate throughout the winter. ear Essex, England, where the studies were made, ater temperatures average 4° to 8° C. during the inter. He reported that the only important seaonal lull occurs just after the spawning season May and that feeding increases again sometime tween September and November. Because he made no controlled laboratory studies of feeding rates at a series of constant temperatures, he could not determine whether the decline in feeding after May was in response to high water temperatures, which rose above 15° C., or to spawning. Thorson (1955) found that the brittle star, *Amphiura* sp., does not feed for 1 month before spawning in late summer; after spawning it lies quiescent on the bottom, not feeding for about another month.

I have attempted to determine feeding rates of starfish at a series of constant temperatures and during different seasons of the year. In the study of seasonal feeding, I wanted especially to obtain a record of possible feeding during winter and to determine whether feeding slows down in midsummer after starfish begin to spawn. Spawning of starfish in Long Island Sound begins in the middle of June and continues intermittently through the summer (Galtsoff and Loosanoff, 1939; Loosanoff, 1961). During the experiments I also recorded the gains and losses in weight of starfish. I believed that such a study would provide important data on the biology of starfish and useful information for commercial growers of shellfish.

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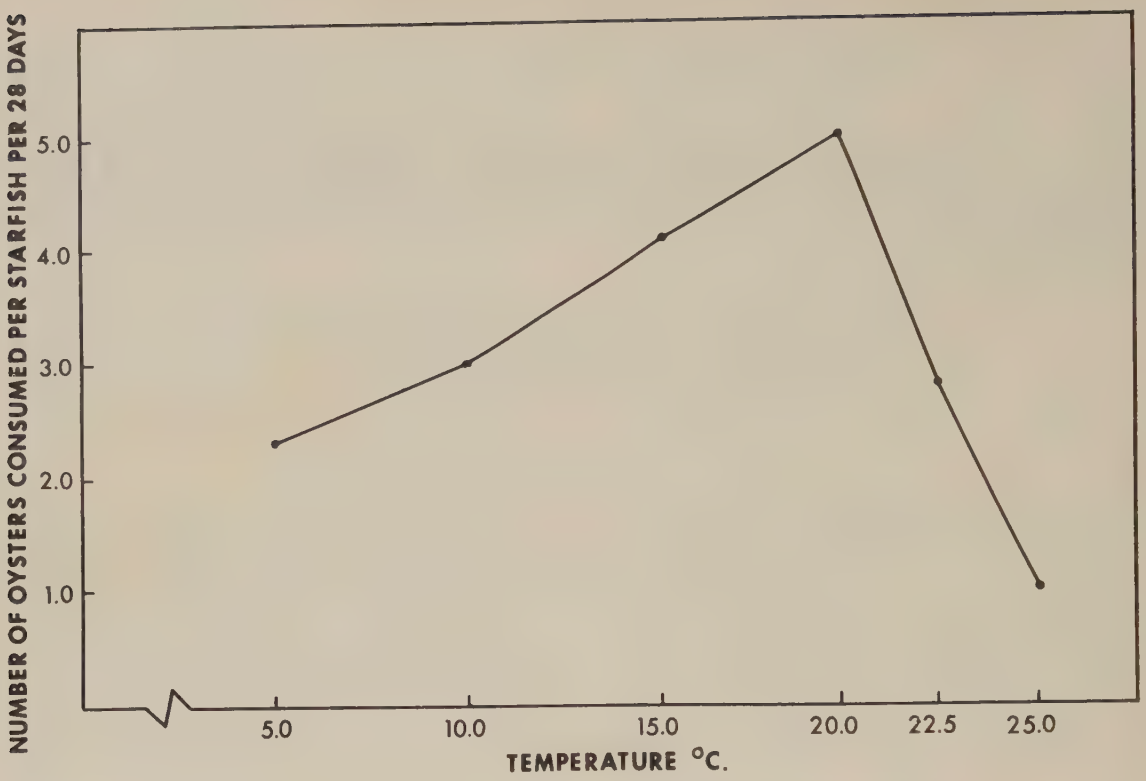

FIGURE 1.—Feeding rates of starfish on oysters at constant temperatures. (Points are based on combined data of replicates at each temperature level—see table 1.)

FEEDING RATES AT CONSTANT TEMPERATURES

METHODS

For the feeding experiments with starfish held at constant temperatures, wooden frames, constructed to hold a bank of four enamel trays (6 cm. by 43 cm. by 50.5 cm.), were arranged on laboratory tables. Each bank was supplied with a separate, continuous flow of sea water. By mixing cold and heated sea water in glass cylinders just above the frames, we maintained the water in the trays within ±1° C. of the temperature desired.

I believe the range of salinity of the water (26.8‰–28.2‰), which corresponds with that of the natural habitat of starfish near Milford, Conn., did not significantly influence the feeding rates during the experiment.

At each temperature four or eight trays were used, each containing 3 adult starfish and 40 oysters. The starfish weighed between 39 and 41 g. (starfish were drained individually for 30 seconds before weighing) and averaged 64 mm. (range 53–75 mm.) from tip of two arms nearest the madreporite to the madreporite. The heights of the oysters averaged about 50 mm. (range 34–80 mm.). Some oysters were in clusters, and others were individuals. To ensure an ample food supply for the starfish, shells of consumed oysters were removed nearly every day and replaced by live oysters.

A fresh group of starfish was obtained in Long Island Sound off Milford for each repetition of a 28-day test at a series of temperatures. These animals were placed in large containers of water at the same temperatures as when they were collected. As the water temperature gradually rose indoors to the point desired, starfish were placed in the experimental feeding trays maintained at this temperature. Oysters, acclimated to the experimental temperature in the same way, were placed in trays with the starfish 1 or 2 days later. Only one starfish died in pans in which water temperatures ranged from 5° to 22.5° C. At 25° C., however, 14 of 72 starfish died during the experiments and one additional starfish lost an arm.

RESULTS

Feeding rates are expressed as the number of oysters consumed per starfish during the 28 days

of feeding. Only one test was made at 5° C. (because low temperatures could not be maintained during late spring); three each at 10° C., 15° C., and 20° C.; one at 22.5° C.; and four at 25° C. Results obtained during replicate tests at the same temperature were similar (table 1).

The rate of feeding was strongly influenced by the temperature of the water. At 5° C. starfish consumed an average of 2.3 oysters each during the 28-day period. The rate of feeding increased by about 1 oyster for each 5° C. increase to 20° C.—to 3.0 oysters per starfish at 10° C., 4.1 at 15° C., and 5.0 at 20° C.; it then decreased to 2.8 at 22.5° C. and 1.0 at 25° C. (fig. 1). Thus, the optimum temperature for feeding of starfish on oysters was 20° C.

Additional observations showed that frequently two starfish and sometimes all three in a pan fed simultaneously on the same oyster or group of oysters in a cluster. Starfish did not always consume all the tissues of oysters they killed; a small amount often remained near the hinge of the oyster after a starfish had left it.

TABLE 1.—*Feeding rates of* A. forbesi *on oysters, height about 50 mm. (range 34–80 mm.), at a series of controlled water temperatures. Rates are given as the average number of oysters consumed per starfish in 28 days*

Temperature and test number	Starfish used in test	Oysters consumed	
		Total	Per starfish
5.0° C.	*Number*	*Number*	*Number*
1	12	27	2.3
10.0° C.			
1	12	35	2.9
2	12	32	2.7
3	24	78	3.2
15.0° C.			
1	12	57	4.7
2	12	47	3.9
3	24	94	3.9
20.0° C.			
1	12	62	5.2
2	24	116	4.8
3	24	120	5.0
22.5° C.			
1	24	67	2.8
25.0° C.			
1	12	18	1.5
2	12	13	1.1
3	24	29	1.2
4	24	12	.5

Besides observing feeding rates of starfish, I measured changes in their weight during 28-day test periods. Average gains in weight were 4.4 g. at 5° C., 7.1 g. at 10° C., 13 g. at 15° C., 13.7 g. at 20° C., and 5.8 g. at 22.5° C. At 25° C. starfish lost an average of 6.5 g. (fig. 2).

The loss in weight by starfish held at 25° C., even though they consumed food, shows that if starfish were held at this temperature for an extended period of time, they would probably die. In figure 2 the line connecting the number of grams gained or lost by starfish supplied with food crosses the point where no weight is gained or lost at about 23.5° C. It would seem, therefore, that starfish from Long Island Sound would probably die if they were maintained for a long period at temperatures above 23.5° C.

As controls in the weight studies, starfish were held in three different situations without food. Nine starfish held in a laboratory tray without food for 28 days at 15° C. lost an average of 7.1 g., and 12 held at 25° C. lost an average of 8.6 g. (fig. 2). Twelve starfish held in a small plastic screen cage in Milford Harbor from April 1 to 30, 1965, when the temperature averaged 5.8° C. (range 2.7–9.5° C.), lost an average of 3.2 g.

FEEDING RATES DURING DIFFERENT SEASONS

METHODS

To study feeding rates during different seasons, trays, measuring 14 cm. by 83 cm. by 147 cm., were suspended from the laboratory dock in Milford Harbor. They were covered and lined on the inside with plastic screening (mesh size 3 holes to the cm.). Depths of water over the trays ranged from 0.75 m. at low tide to 2.5 m. at high tide. Each tray held 20 adult starfish and 140 oysters. From January 20, 1964 to January 26, 1967, one tray was examined once every 2 to 4 weeks. An examination consisted of lifting the tray out of water, placing the starfish in buckets of water, washing the tray with a hose, counting the oysters consumed by starfish, replacing them with live oysters of the same size, returning the starfish to the tray, and then lowering the tray to its normal position.

From May 17, 1966 to January 26, 1967, a period of slightly more than 8 months, a second tray similar to the first was examined in the same manner on each date, except that after each examination the starfish and oysters were transferred to a clean replacement tray. This procedure was followed to ensure that starfish were not consuming large fouling organisms, which might have set in the tray, rather than the added oysters, thereby giving a false indication of their rate of feeding.

RESULTS

Starfish in trays suspended in Milford Harbor displayed the same pattern of feeding in each of the 3 years of observations (fig. 3). The rate of

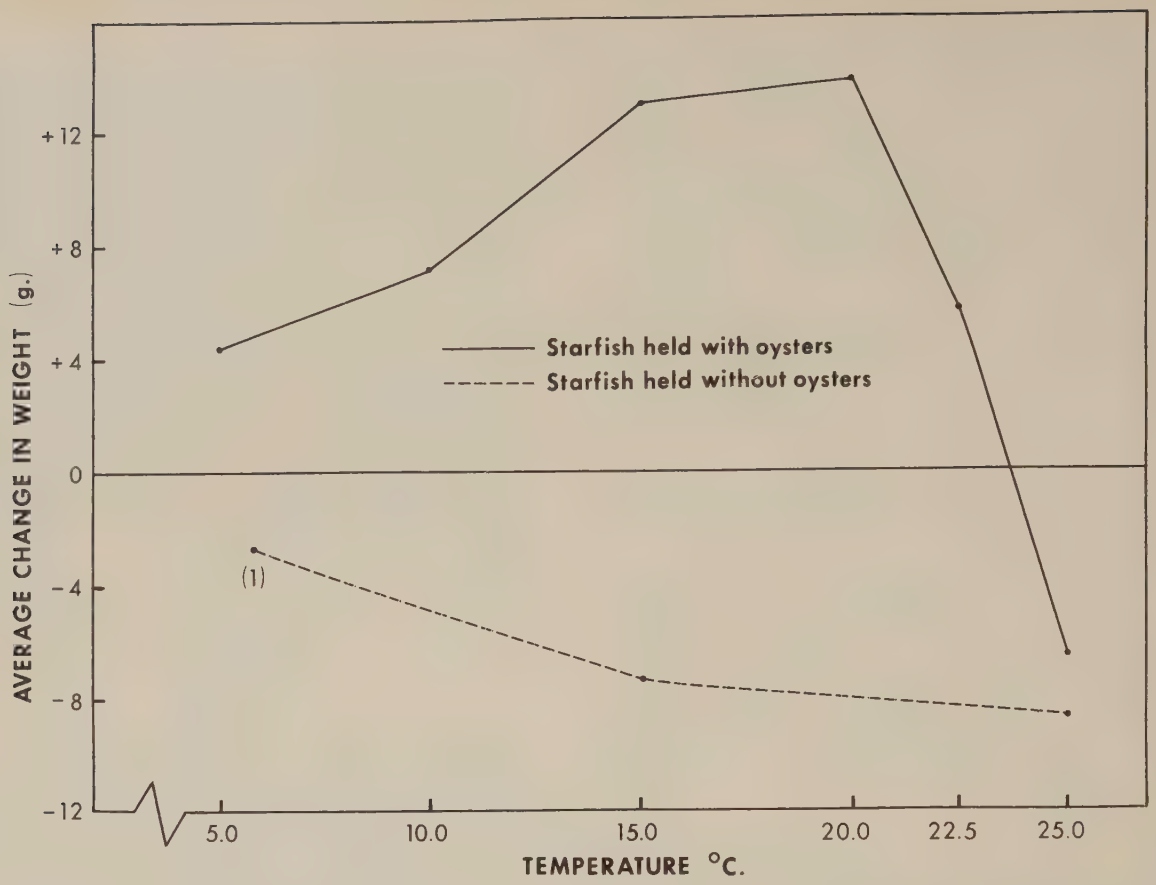

FIGURE 2.—Average weight change of starfish held at constant temperatures for 28 days, with and without food. (Points are based on combined data of replicates at each temperature.) Point (1) represents starfish held in a cage in Milford Harbor, April 1–30, when temperatures averaged 5.8° C. (range 2.7–9.5° C.).

feeding was low from mid-January until the end of March. For example, in 1965 the 20 starfish consumed about 0.6 oyster per 7 days (0.12 oyster per starfish per 28 days) during this period of 2.5 months. From mid-April to late June and early July the rate rose sharply, apparently as a result of the rise in water temperature. At the time of most intense feeding, in late June 1965, the 20 starfish ate about 20 oysters per 7 days (four oysters per starfish per 28 days). In late July, August, and September the rate of feeding decreased to about a third of its level in late June and early July. In late October, November, and early December the rate increased again to about two-thirds of the rate in late June and early July. Beginning in late December, feeding rates began to decline but did not really become low in 1965 and 1966 until mid-January. In 1967, however, because of unusually warm water, feeding had not declined to its previous winter low by late January when observations were terminated.

As the experiment continued from 1964 through 1966, the starfish grew larger. The new group of oysters collected each spring was, however, of about the same average size—50 to 65 mm. (range 34–82 mm.)—as the original group fed to the starfish in 1964. Because the larger starfish consumed more oysters (of a particular size) than the smaller ones, feeding rates were higher in each successive year.

The feeding in the second tray, observed from May 17, 1966 to January 26, 1967 (to evaluate the effect of possible consumption of fouling organisms on feeding rate), was essentially similar to that in the first tray. Because the supply of oysters was low, however, it was necessary to use smaller oysters in this tray after late August. The starfish in this second tray, consequently, showed a much higher consumption of oysters than did those in the first tray which were feeding on larger oysters (fig. 3).

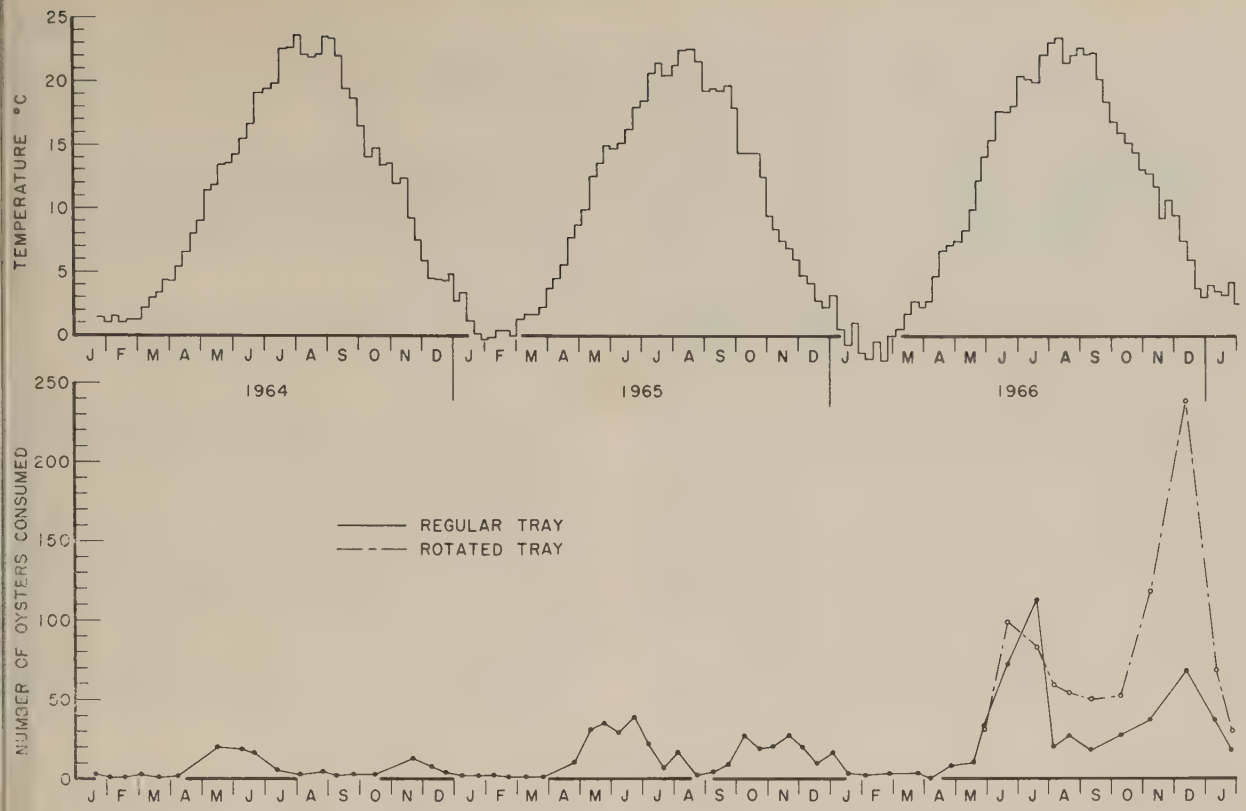

FIGURE 3.—Number of oysters consumed by 20 adult starfish held with 140 oysters in a tray from January 1964 to January 1967 and (in a second tray) from May 1966 to January 1967. Both trays were suspended in Milford Harbor. Temperatures are given in the upper panel.

In 1964, 1965, and 1966, during the period of ittle feeding from mid-January to the end of Iarch, water temperatures averaged 1° C. (range -2.2° to 3.2° C.). Observations of starfish in trays n Milford Harbor and of those dredged from the ottom showed that they feed on oysters and other ood at temperatures at least as low as 0.2° C. Temperatures increased to 7° to 9° C. by the end f April, to 13.5° to 15° C. by the end of May, nd to 18.5° to 19.5° C. by the end of June (when ne rates of feeding were highest). By mid-to-late uly temperatures reached 22.5° C. and stayed t or above that level until early or mid-Septem- er (during the period when rates of feeding were bout a third as intense as they were in the spring). n the 3 years temperatures averaged 13.5° to 15.3° C. during October, 7.9° to 11.6° C. during Novem- er, and 3.6° to 5.8° C. during December, and dur- ng this period of 3 months feeding rates were bout two-thirds as intense as they were in late une.

SUMMARY OF EFFECTS OF WATER TEMPERATURES AND SEASONS ON FEEDING RATE

A comparison of feeding rates of starfish at constant temperatures with those in different seasons shows that the rates in different seasons are controlled primarily by seasonal temperatures. Though laboratory studies were not conducted to determine feeding rates at temperatures below 5° C., low rates from mid-January to the end of March are undoubtedly a result of temperatures which average only 1° C. As temperatures rise in the spring to nearly 20° C., the optimum temperature for feeding, by the end of June feeding increases rapidly.

In summer the decline in feeding coincided with high temperatures. For example, in 1964 temperatures exceeded 22.5° C., the temperature at which feeding probably begins to decline, on July 15, about 2 weeks after a sharp decline in feeding had already begun. In 1965 temperatures rose to above 22.5° C. for only a few days during July, coincid-

ing with the decline in feeding. In 1966 temperatures rose above 22.5° C. on July 7 shortly before feeding declined. In 1964, because feeding began to slow down before temperatures reached 22.5° C. and continued low in late September and early October after temperatures dropped well below 22.5° C., some other factor—probably the effects of spawning which started in mid-June—seemed to be partly responsible for the low feeding rate. In 1965, the possible effects of spawning were observed through September because feeding was low even though temperatures were 16° to 21° C. In 1966, low feeding was recorded from mid-September through early October when temperatures ranged from 16° to 22.5° C. The rate of feeding increased again in late October and remained high through most of November as temperatures dropped to 15° C. and lower. Feeding rates declined in late December when temperatures fell to 2° to 4° C. and reached the winter low by mid-January when the temperature fell to about 1° C.

Asterias forbesi in Long Island Sound exhibits a reduction in feeding in midsummer similar to that reported by Needler (1941) for *A. vulgaris* in Eastern Canada and by Hancock (1955, 1958) for *A. rubens* in English waters. In contrast to *Amphiura* sp., as described by Thorson (1955), *A. forbesi* apparently feeds actively right up to the time it spawns.

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Barry Baiardi, Russell Clark, and Otis Lane provided technical assistance, and Herman R. Glas collected starfish.

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FACTORS INFLUENCING THE ATTRACTION OF ATLANTIC HERRING, *CLUPEA HARENGUS HARENGUS*, TO ARTIFICIAL LIGHTS

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ABSTRACT

Using artificial lights to attract fish at night is a common and often effective fishing technique. With Atlantic herring the attraction is somewhat uncertain, however, and does not always take place. This paper describes experiments which showed that, in addition to the inherent variability of the fish themselves, certain external conditions can modify the attraction to the light. Attraction was greater at low than at high temperatures, greater with underwater lights than with lights above the surface, and greater when the fish were previously adapted to light than when they were adapted to darkness. Very bright light (illumination 20–600 lux), especially above the surface, tended to repel the fish. Light of intermediate intensity (illumination 1–30 lux) was most effective.

The behavioral responses comprised an initial attraction resembling positive phototaxis, followed by apparent disorientation, or confusion. The disorientation may have been due to attempts by the fish to respond with a dorsal light reaction, i.e. to assume postures which would orient their dorsal surface toward the light source even when such postures interfered with normal swimming.

The use of artificial lights for attracting fish is a common practice in fisheries throughout the world. The methods have changed but little, however, the chief improvement being the substitution of electric light sources for open flames or fuel-burning lamps.

The attraction of Atlantic herring (*Clupea harengus harengus*) with lights has been studied experimentally and adapted to some extent for commercial fishing. Lights have been used routinely on Norwegian purse seiners for many years to attract herring. According to Dragesund (1958), herring are not always attracted to lights, however, and even the fishermen do not agree about the behavior of herring in response to the lights used on seiners. Dragesund studied the behavior of fish schools from a research vessel and distinguished the following kinds of reaction to the attracting light:

1. Fish descend and pack together.
2. Fish disperse.
3. Fish rise toward light, then shortly descend.
4. Fish pack together, then rise toward the light.

Blaxter and Parrish (1958) were able to attract young herring (5–25 cm.) to underwater lights at several levels of brightness and to bring them to the surface by raising the lights. Tibbo (1965) reported that herring in a large tank were attracted to artificial lights of various intensities and colors, although they were repelled at the highest intensities. Gauthier (in press), collaborating with fishermen on a commercial purse seiner, reported catches of herring of 25 to 40 tons in trials with underwater lights in the Gulf of St. Lawrence.

Lights were used traditionally along the Atlantic Coast of North America for catching juvenile herring by "torching," a method probably adopted from the Indians. A kerosene- or gasoline-burning flare, or even a more primitive torch of combustible material on a stick, was mounted on the bow of a small boat. The procedure has been described by Earll (1887) as follows. "The fishermen usually go to the shore late in the afternoon and time their departure so as to reach the fishing grounds shortly after sunset. As soon as it becomes sufficiently dark, the fire is lighted, one man takes his position in the stern to steer the boat and another stations himself in the bow, armed with a dip-net for securing the fish as they gather in little bunches just in front of the light. The remaining members of the crew row the boat rapidly through the water, while the man in the bow is busily engaged in throwing the fish into the boat

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by means of his dip-net. Great numbers of herring are attracted by the light and it is not uncommon for fifteen or twenty barrels to be taken in a few hours."

The variability of the herring's response to light is a characteristic feature and has been noted by many investigators. Blaxter and Holliday (1963) stated ". . . . Such reactions will vary widely depending on the environment and the physiological state and age of the fish as well as on the type of stimulus itself." Other authors have demonstrated how many factors, external and internal, can vary the response of herring and other species to artificial lights. Kurc (in press) and others have pointed out how the thermocline may prevent fish from rising to a light, or may hold them in the surface water so that they can be more readily attracted. Strong ambient light (e.g. moonlight) may reduce the effectiveness of the attracting light (Kurc, in press; Ström, in press). Woodhead (1956) showed that starvation reversed the normal negative phototaxis of the minnow *Phoxinus*. Andrews (1946) found that the attraction to light of the white sucker (*Catastomus*) decreased with increasing temperature. Sudden changes in illumination may cause the fish to disperse instead of attracting them (Ström, in press; Gauthier, in press).

Although routine, uncritical use of lights to attract fish may sometimes be successful, far greater effectiveness might be achieved by a better understanding of the underlying behavior of the fish and its response to lights. Moreover, lights might be of definite value in some circumstances where they are not now used. In Maine the use of lights for catching herring is generally illegal because many fishermen believe that the lights tend to disperse the herring rather than attract them (Scattergood and Tibbo, 1959). This restriction appears to be an instance where profitable use of lights has been discouraged because the underlying behavior of the fish has been inadequately understood.

This paper is an attempt to explain some of the biological and other factors that are conducive to the attraction of herring by light.

METHODS

The fish used in the experiments were immature Atlantic herring of age groups O (brit), I, and II, which are processed as Maine sardines. They were 75 to 200 mm. in total length and were taken from commercial catches near Boothbay Harbor, Maine. The fish were held under the prevailing seasonal conditions of salinity, temperature, and dissolved oxygen in large tanks provided with running sea water and were fed daily a mixture of ground trout food and canned cat food.

The experiments were conducted in a separate tank. This tank was fiberglass, 5.5 m. long, 0.4 m. deep, and 0.3 m. wide. An incandescent lamp suspended in a glass cylinder at each end of the tank provided the attracting illumination; by raising or lowering the lamp bulb in the cylinder, the light source could be located above or below the surface. Sea water entered the left-hand end of the tank and drained off at the right. A slight drift (less than 4 cm. per minute) toward the right resulted. This and other sources of left-right bias were compensated by periodically alternating the location of the light source between the right and left ends of the tank with a double throw switch. For temperatures above the seasonal sea-water temperature, the incoming water was heated. An air bubbler near the point of entrance and another near the center of the tank provided sufficient mixing so that temperature differences within the tank did not exceed 1° C. Cooling pipes, carrying a chilled ethylene glycol-water mixture, located along the walls of the tank provided uniform refrigeration when below-seasonal temperatures were required.

Variations in dissolved oxygen were achieved by recirculating the water through a tank of pure oxygen under pressure (1.5–2.0 atmospheres) or through a vacuum. These devices provided a range of 50 percent to 250 percent oxygen saturation in the experimental tank.

The intensity of the attracting lights was varied by using light bulbs of different wattages or by varying the supply voltage. The light gradient for each intensity and source position (fig. 1) was measured with a photovoltaic light meter having a waterproof housing for the sensitive element. This element was held in a plane normal to the direction of the light rays in the water. The meter was factory-calibrated for a spectral response corresponding to that of the human eye. This response is not identical to that given for herring (Blaxter, 1964), but is very similar; the difference was so small that special calibration of the instrument did not seem warranted.

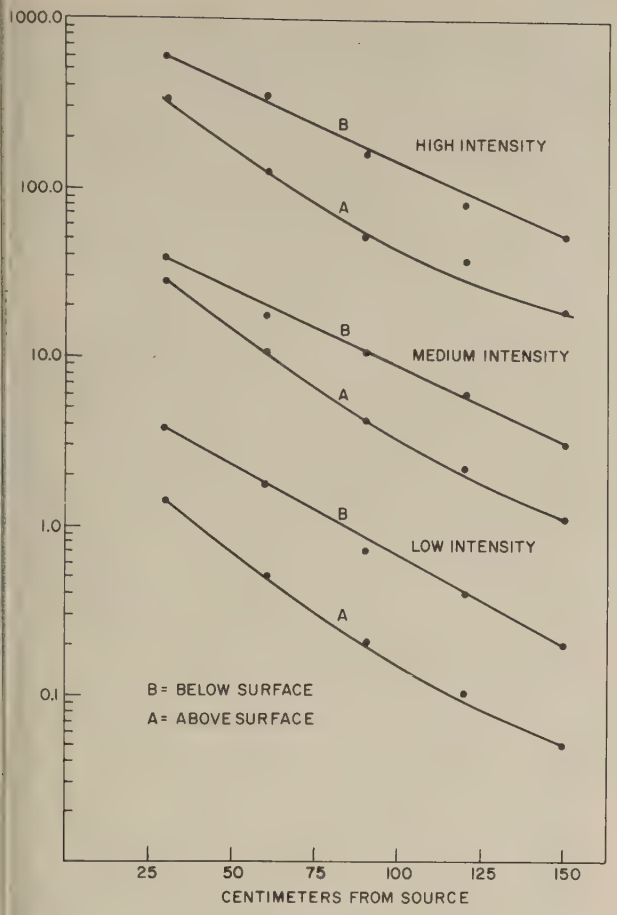

FIGURE 1.—Light gradients at the three light intensities used in the experiments.

The fish were taken at random from a storage tank and transferred to the experimental tank, where they were allowed to accommodate for periods of 30 minutes to 15 hours before each trial. Except where light or dark adaptation was at issue in the experiment, the period preceding each trial was at room illumination. I found no significant difference in the responses of individual herring allowed a half-hour or full-hour period of accommodation to the tank. Once the fish recover from the initial disturbance after transfer, it is not likely that any further time for accommodation is necessary. This factor should not affect the results of the experiments, because for any given experiment the accommodation periods of all fish were the same. Accommodation periods were progressively reduced throughout the series to save time.

No attempt was made to acclimatize the fish to arbitrarily selected temperatures because facilities for this purpose were not available. The fish were transferred from water at seasonal temperatures to the experimental tank. Because temperature acclimatization exerts a definite influence on the subsequent reactions of fish to temperature, it could conceivably affect their response to light at different temperatures. For that reason I have specified the acclimatization (=seasonal) temperature for the fish used in each experiment (table 1). It will be noticed, however, that several combinations of acclimatization and experimental temperatures produced no qualitative difference in the results of experiments where the effect of temperature was being tested.

TABLE 1.—*Summary of pretrial experience of experimental herring*

Experiment number	Accommodation period	Acclimatization temperature	Experimental temperature	
	Hours	*° C.*	*° C.*	*Month*
1	15	5	6, 12, 16	December
2	15	3	5	February
3	1–2	10–13	15–17	October
4	½–2	10–13	15–17	October
5	½–2	10	15–17	October
6	6	5	6, 12, 16	December
7	6	10–14	5–6, 15–17	July
8	3	13–16	8–10, 15–17	July–August
9	5	2–3	4–6	March
10	6	10–14	15. 5–17	June
11	6	10–14	6–9	July
12	6	13–16	15–17. 5	August–September
13	1	13	15–17	October
14	3	3	5	January
15	6	13–16	15–17. 5	August–September
16	1	14–16	15. 5–17	September

An experiment consisted of several trials in which the variables of interest were given predetermined values; each trial could be given a different set of conditions or could replicate another trial. For experimental variables that could be changed quickly (e.g. light location or intensity), several trials were completed in a single day. For conditions that required a longer time to establish (e.g. temperature or gas content), only one trial could be completed in a day, and an experiment might last several weeks. In protracted experiments of this sort, when only two treatments were involved, the trials were alternated; when several were involved in the same experiment, the trials were ordered randomly.

Two routine procedures were used. When fish were tested singly (experiments 1 to 4), the attracting light was turned on at the right end of the tank for 5 minutes, and the amount of time spent by the fish in the illuminated half of the

tank recorded. Then the illumination was switched to the left end of the tank and the time spent in that half by the fish was recorded. The illuminated half of the tank was reversed end for end every 5 minutes over 30-minute periods. The score by which the attraction to light was measured was the cumulative amount of time spent by the fish in the illuminated half of the tank.

The second routine procedure was used whenever a group of fish were tested (experiments 5 to 16). Ten randomly selected herring were placed in the tank, the attracting light on the right was turned on, and the number of fish present in the illuminated half was counted each minute for 5 minutes. The illumination was then switched to the left side, and the fish present in the illuminated half of the tank were again counted each minute for 5 minutes. The lights were, thus, alternated from end to end at 5-minute intervals until 30 counts had been made. The sum of the 30 counts was the score for groups of fish. A variant of this procedure was used in two experiments (13 and 16). Each trial lasted only 1 minute, and counts were made at 15, 30, 45, and 60 seconds. The light position remained the same throughout the period of one trial, but equal numbers of trials were made with the left side illuminated and with the right side illuminated.

In no experiment were the same fish used in successive trials; after being used once, every fish was returned to a separate holding tank and was not used again for at least 2 weeks.

Comparisons of scores between only two conditions were analyzed statistically with a "t"-test; comparisons among several kinds and levels of treatment were analyzed with a fixed-model analysis of variance.

GENERAL BEHAVIOR

After the fish had become accustomed to the experimental tank their behavior stabilized into one of three general patterns: (1) swimming regularly back and forth from one end of the tank to the other (in a loose school, if in a group), (2) remaining at one end of the tank, or (3) milling about randomly throughout the tank. After the room was darkened and the attracting light was turned on, whatever behavior pattern had been adopted by that particular fish or group of fish continued; this behavior tended to obscure the response of the herring to the attracting light. Although a brief flurry of activity near the lamp frequently occurred at the begining of each trial, the degree of attraction was not obvious by casual observation; it could be demonstrated only by repeated counts over an extended period. The fish showed no tendency to gather in any locality of optimum light intensity.

The exact behavioral mechanisms involved in the attraction of fish to artificial lights are not known, although several theories have been proposed, ranging from a straightforward positive phototaxis to a conditioned response where light is associated with food. One of the more interesting theories is that of Verheijen (1959 and in press). He suggested that an artificial light creates an unnatural light field which leads to a disoriented behavior of the fish, because "such simplified visual environments" may not "deliver adequate information to all integration levels involved in the performance of the fish's natural behavior." The net effect is one of trapping fish rather than merely attracting them.

Close observation of herring in some of my own experiments yielded clues about their behavior in an unnatural light field which may amplify somewhat the ideas of Verheijen. The typical behavior of a single herring consisted of the following events:

(1) Starting from the dark half of the tank, the fish swims slowly at first, then with increasing speed directly toward the light.

(2) Upon reaching the light, sometimes striking it squarely with its snout, the fish turns more or less broadside to it and proceeds to circle it, or swim to and fro in short courses which lie generally along the circumference of a circle around it.

(3) This behavior is frequently interrupted by movements which give the impression of confusion or disorientation. Close observation indicates that these movements are, in fact, attempts by the fish to orient its dorsal surface toward the light source. When the light is under water, these attempts lead the fish to assume momentarily vertical postures or horizontal postures on its side with its back toward the light.

(4) In retreating from the light, the fish swims in a zigzag course, the legs of which become progressively more nearly perpendicular to the direction of the light, and the fish eventually returns to it; or the legs become progressively more oblique and the fish escapes into the darkened zone.

(5) After a short stay in the dark zone, the fish repeats the entire procedure.

Many of these actions appear to be manifestations of the "dorsal light reaction" (Frankel and Gunn, 1961) in which a fish orients itself in a position so that its dorsal surface is more or less perpendicular to the direction of the light rays. Woodhead and Woodhead (1955) have described such a phenomenon in herring larvae. Under natural lighting, where the predominant direction of the light is downward, the herring can orient to the rays in its normal swimming posture, descending when the light is too strong, and rising when it decreases. When a single light source is close to the surface or beneath it, phototaxis can take place with no departure from the normal swimming posture, but dorsal orientation to the light (except when the fish is directly beneath it) requires postures that interfere with normal swimming—hence, the apparent disorientation and difficulty in escaping the influence of the light.

VARIATION IN SUSCEPTIBILITY TO LIGHT ATTRACTION

Whatever may be the effect of external conditions in modifying the response of herring to light, individual differences among the fish lead to wide variation in this response even under identical external conditions. This variability is illustrated by five experiments.

FREQUENCY DISTRIBUTION OF THE RESPONSE TO LIGHT OF INDIVIDUAL FISH

Individual fish vary in behavior as well as physical characteristics. If this variation were reasonably close to a normal distribution, the statistical treatment used in this study would be more likely to be valid than if the variation was not normally distributed. The following experiment was made to examine the variation among individual fish.

Experiment 1. Ninety herring, selected at random, were observed individually to determine the degree to which they were attracted to an underwater light of medium intensity; 30 were observed at 6° C., 30 at 12° C., and 30 at 16° C. Scoring was based on the amount of time spent in the illuminated half of the tank. The mean scores of 16.2, 17.2, and 17.8 at 6°, 12°, and 16° C., respectively, were not significantly different ($F=0.92$, $P>0.1$). The three frequency distributions each showed a reasonable tendency toward normality (fig. 2). When all the scores were combined, this tendency was more pronounced (fig. 2, dashed line).

CHANGES IN SUSCEPTIBILITY TO LIGHT ATTRACTION

If herring differ from individual to individual in their susceptibility to light attraction, do individuals vary in themselves over a period of time?

Experiment 2. To answer this question, 25 herring were fin clipped to identify individuals and tested and scored as in the preceding experiment.

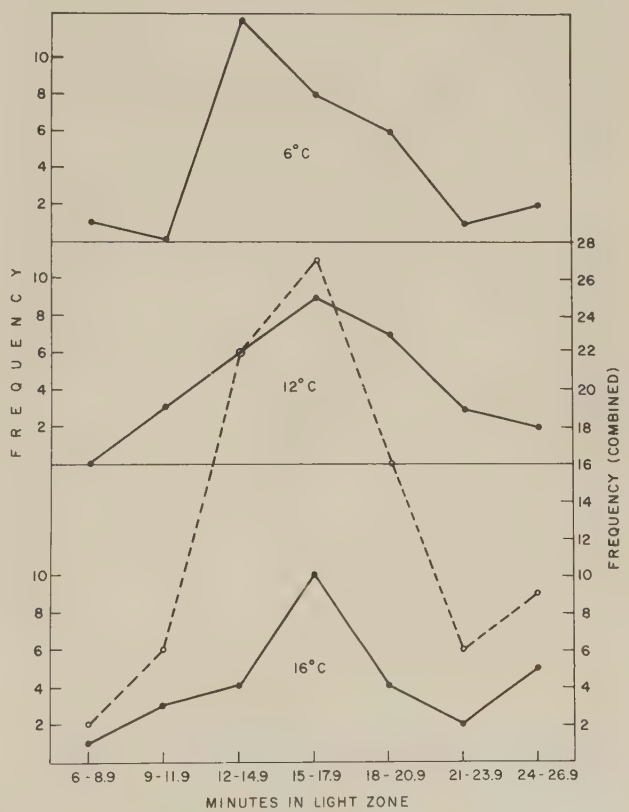

FIGURE 2.—Frequency distribution of scores (experiment 1) based on the time in minutes out of a possible 30 minutes spent by individual herring in the illuminated half of a tank. Solid lines, distribution of scores at each of three temperatures; dashed line, distribution of all scores, regardless of temperature.

They were then transferred to another tank and left undisturbed for 1 week. After this interval they were again scored as before. (Two of these fish died in the interval, so that data from only 23 were complete.)

If the degree of response is a fixed characteristic, the response should be the same on the second occasion as on the first, or if a change has occurred, it should affect all the fish more or less similarly, so that a high degree of correlation should be found between the scores in the first test and the scores in the second. Actually, some fish increased their scores and some decreased them (table 2); some changed from a positive response (more than half the time spent in the lighted zone) to a negative one. The correlation coefficient of $R=0.55$ was very weak, although it was barely significant. This result can be interpreted to mean that although individuals tend to maintain a certain inherent response characteristic, this characteristic may vary substantially with time.

TABLE 2.—*Scores (number of minutes spent in illuminated half of tank) for individual herring in two 30-minute tests, 1 week apart (experiment 2)*

First score (by rank)	Score 1 week later
Minutes	*Minutes*
25.27	16.18
24.17	19.05
23.18	16.45
21.90	19.32
21.02	19.35
20.57	20.58
20.03	14.15
19.03	18.08
18.98	10.70
18.62	15.43
18.13	14.53
18.08	14.80
17.77	19.37
17.73	18.05
15.82	16.78
15.50	17.98
14.82	20.85
14.17	8.45
14.08	13.88
13.05	9.97
12.48	7.35
12.12	13.20
12.08	11.03

EFFECT OF CONDITION ON SUSCEPTIBILITY TO LIGHT ATTRACTION

There may be many possible reasons for the variability in response among individual fish. Three reasons which readily suggest themselves are differences in sex, physical condition, and age. I did not attempt to determine the effect of sex experimentally because of the need for economy in use of specimens; determination of sex requires killing the fish. Evidence that strong sex differences occur, however, does not show in the frequency distribution of responses. If males and females differed greatly in response, one would expect some indication of bimodality to the distribution.

Experiment 3. To determine the effect of condition, 32 herring were tested individually at 15 to 17° C., and the time spent in the illuminated zone was recorded for each 30-minute trial. The medium-brilliance, subsurface illumination was reversed end for end every 5 minutes according to the routine procedure. Half of the herring were in excellent physical condition and half were starved and emaciated. The mean scores of 18.1 for the fish in good condition and 18.9 for those in poor condition were not significantly different ($F=0.22$).

EFFECT OF AGE ON SUSCEPTIBILITY TO LIGHT ATTRACTION

Two experiments were done to determine whether any differences in attraction to light could be attributed to the age of the herring; the first of these dealt with individual fish, the second with groups of fish.

Experiment 4. Nineteen herring in age group O and an equal number in age group I were tested individually according to the same procedure used in experiment 3. The mean scores of 20.4 for the O-group fish and 19.5 for the I-group fish were not significantly different ($t = 0.59$).

Experiment 5. Herring of age group O and age group I were tested in groups of 10 individuals according to the second routine procedure described under "Methods." The scores were based on the number of fish counted each minute for 30 minutes in the illuminated half of the tank, which was reversed end for end every 5 minutes. The mean scores for 10 trials with each age group were 120 for the O-group and 132 for the I-group fish; the difference was not significant ($F < 1.0$).

EFFECTS OF EXTERNAL VARIABLES ON THE ATTRACTION OF HERRING TO LIGHT

EFFECT OF TEMPERATURE

The experiments in the preceding section dealt primarily with variables inherent in the fish themselves. In this and following sections the experiments deal chiefly with external variables. Evidence from experiment 1 indicated that temperature had little effect on the attraction to light of individual fish. The experiments in the present

ection involve groups of fish and, as will be seen, emperature does exert a definite effect on herring n groups.

Experiment 6 (cf. experiment 1). Ninety her- ng, selected at random, were tested in groups of) individuals at three temperatures: 6°, 12°, and 6° C. Three trials were made at each temperature. The scores of 205, 129, and 121 at the three tem- eratures, respectively, were significantly different F=6.19, P <0.05).

Experiment 7. The purpose and methods of this xperiment were similar to those in experiment 6, xcept that only two temperature levels were pro- ided and these on alternate days. In the previous xperiment, trials at low temperature were made rst, followed by trials at the two higher emperatures.

Five trials were made at temperatures of 5 to ° C. and five at 15 to 17° C. The fish were taken rom storage at 10 to 14° C. and held 6 hours at he experimental temperature before each trial. The mean scores were 201 at low temperature and 29 at high temperature (table 3). If the scores re treated simply as two sets of five observations, he difference in means is of marginal significance t=2.04, P=0.075); if the scores are treated as ve sets of paired observations, however, t=10.1 nd the differences are highly significant. Because he low-temperature score for each trial was con- istently higher than the immediately following igh-temperature score, the analysis as paired ob- ervations seems reasonable, and the hypothesis hat lower temperature increases the attraction to ght is confirmed.

TABLE 3.—*Comparison of scores*[1] *for light attraction of herring at low and high temperatures (experiment 7)*

	Temp.	Score	Temp.	Score
	° C.		° C.	
	5.2	180	15.4	120
	5.7	234	16.5	155
	5.5	198	15.2	139
	5.5	179	16.2	115
	5.7	214	16.2	119
eans	5.5	201	15.9	129

[1] Score=sum of numbers of herring counted in the illuminated half of he tank at 30 1-minute intervals. Ten herring were used in each test; maxi- um possible score=300.

FFECTS OF TEMPERATURE, LIGHT INTENSITY, AND LIGHT POSITION

Experiment 8. The responses of groups of 10 erring were observed at two temperature levels (8–10° and 15–17° C.), at three levels of light intensity (fig. 1), and with the attracting light either above or below the surface. Each combination of conditions was replicated once. The fish were taken from storage at 13 to 16° C. and held 3 hours at the experimental temperature before each trial. Table 4 shows the scores. The differences in response were highly significant between high and low temperature (F=69.2) and between above- and below-surface lights (F=48.7). There was also a significant interaction between light position and intensity, such that the bright light above the surface had the poorest attraction and the bright and medium lights below the surface had the greatest. The difference in response due to position of the light was significantly greater at low temperature. In general, below-surface lights were more effective at low temperature than at high.

ATTENUATION OF LIGHT ATTRACTION WITH TIME

Experiment 9. The degree to which light will hold the herring in its vicinity is a significant component of the total attraction to light. This experiment was intended to determine whether this holding effect would decrease with time, and, if so, whether such decrease was affected by light intensity or position.

TABLE 4.—*Comparison of scores*[1] *for light attraction of herring in relation to light location, light intensity, and temperature (experiment 8)*

Light intensity	High temperature (15–17° C.)		Low temperature (8–10° C.)		Mean score
	Light above surface	Light below surface	Light above surface	Light below surface	
High	135	254	122	166	146
	100	254	159	139	
Medium	192	230	159	179	167
	163	229	150	180	
Low	186	212	149	172	159
	180	217	151	164	
Mean score	159	232	148	167	

[1] Score=sum of numbers of herring counted in the illuminated half of the tank at 30 1-minute intervals. Ten herring were used in each test; maximum possible score=300.

The experiment comprised 24 trials. Each trial consisted of three phases: the first, a 30-minute series of counts on a group of 10 fish, the same as the routine procedure used in other experiments; the second, an 18-hour interval with the attracting light left on; and the third, another 30-minute series of counts like the first. The 24 trials repre-

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sented three levels of light intensity (high, medium, and low) and two light positions (above and below the surface). Each combination of lighting characteristics was replicated four times—two with the light on the left during the 18-hour interim and two with the light on the right. Table 5 gives the scores of the trials, before and after the 18-hour interim. The number of fish in the lighted zone was reduced significantly after 18 hours ($F=13.4$, $P<0.01$). This reduction was significantly greater when the lights were above the surface ($F=11.83$, $P<0.01$) than when the lights were below, but the differences in reduction associated with light intensity were not significant.

TABLE 5.—*Comparison of scores*[1] *for light attraction before and after an 18-hour interval of constant stimulus, in relation to light location and intensity (experiment 9)*

Light intensity	Before interval			After interval		
	Light above surface	Light below surface	Mean	Light above surface	Light below surface	Mean
High	109	138	134	94	130	109
	144	132		80	125	
	109	133		57	114	
	158	149		126	147	
Medium	127	209	154	80	230	133
	177	138		101	149	
	119	188		76	186	
	103	172		87	157	
Low	143	136	151	97	90	117
	224	139		136	90	
	163	133		136	143	
	147	127		138	114	
Mean	143	149		101	139	

[1] Score = sum of numbers of herring counted in the illuminated half of the tank at 30 1-minute intervals. Ten herring were used in each test; maximum possible score = 300.

EFFECT OF OXYGEN CONCENTRATION

The possible importance of oxygen concentration to the light response was suggested partly by observations that the habitat of juvenile herring was frequently supersaturated with oxygen in summer (Colton, Marak, Nickerson, and Stoddard, 1968; Stickney, 1968) and partly by a comment of Kalle (1965) that the vertical migration of herring (usually considered a response to light) might be due to depletion of oxygen in dense schools near the bottom.

Experiment 10. Groups of 10 herring were tested on alternate days in water normally saturated or highly supersaturated with oxygen before each trial. The temperature of the experiment was 15.5 to 17° C.; the mean oxygen levels were 8.1 p.p.m. (98 percent saturation) and 17.2 p.p.m. (212 percent saturation). The herring were taken from storage at 11 to 14° C., 110 to 125 percent 0_2 saturation. Each trial consisted of the routine exposure to an attracting light; scores were based on the number of fish counted each minute for 30 minutes in the lighted end of the tank. The mean score for six trials in normal water was 122; that for six trials in supersaturated water was 164. The difference had a "t" value of 2.04 ($P<0.1$); treated as paired data, the differences between each pair of trial scores had a "t" value of 4.28 ($P<0.01$). The experiment seemed to indicate that supersaturation had a significant effect on the attraction of the herring to light. Subsequent experiments (11 to 13) did not corroborate these results, however.

Experiment 11. Herring were taken from holding tanks at 10 to 14° C. and 105 to 130 percent saturation of oxygen and held 6 hours under the experimental conditions before each trial. Normally saturated and supersaturated water averaging 9.6 p.p.m. (93 percent saturation) and 19.7 p.p.m. (185 percent saturation) of oxygen, respectively, at 6 to 9° C. were provided on alternate days. In five trials at each oxygen level, mean scores were 198 in the normal water, 205 in the supersaturated water. The difference is not significant ($t=0.43$).

Experiment 12. This experiment was actually a part of experiment 15 and included the additional variable of light-dark adaptation. The three levels of oxygen concentration were low (mean=5.3 p.p.m., 63 percent saturation), saturated (mean =7.9 p.p.m., 93 percent saturation), and supersaturated (mean=21.8 p.p.m., 240 percent saturation). Herring which had been adapted 6 hours to light or darkness before each trial were tested at each level of oxygen, making six combinations of experimental variables, each combination replicated five times. The herring were taken from storage at 12 to 17° C. and 100 to 124 percent saturation of oxygen and exposed 6 hours to the experimental conditions before each trial. The mean scores for ten trials at each level of oxygen were 125, 138, and 123. The difference among them was not significant ($F=0.7$).

Experiment 13. The effects of light or dark adaptation were most pronounced during the first minute of exposure to the attracting light. Because this critical time period may not have been ade-

ately monitored in the other experiments with ygen concentration, observations were made on oups of 10 fish 15, 30, 45, and 60 seconds after e attracting light was turned on. The location the light was alternated between right and left th each trial. Four trials were made each day; rmally saturated and supersaturated water were ed on alternate days. The sequence was repeated ice, making eight trials at each oxygen level, all a mean temperature of 15.5 to 17.0° C., and mean ygen concentrations of 7.3 p.p.m., 88 percent uration and 16.8 p.p.m., 200 percent saturation. he mean scores of 31 and 29 were not significantly fferent.

The weight of evidence indicates that neither ygen concentration nor percentage saturation s any effect on the attraction of herring to light.

EFFECT OF PREVIOUS ADAPTATION

Experiment 14. Preliminary observations showed endency for herring to be less strongly attracted light if they had been kept in darkness beforend. Therefore, for most of the experiments the rring had been held in full room illumination that their response would be as strong as posble. Nevertheless, some specific tests seemed derable to confirm the preliminary observations. Sixteen trials, two each day, were made with oups of 10 herring at a temperature of 5° C. ach group was exposed to a medium-intensity, nderwater light after a 3-hour period of adaptaon to light or darkness just before each trial. hese adaptation periods were alternated with reect to time of day, forenoon or afternoon.

Because the fish had necessarily to be held at all mes other than the 3-hour adaptation period at me lighting condition or another, the possibility isted that whatever this lighting was would also fluence the subsequent behavior of the fish. herefore, half of the trials were preceded with xposure to total darkness the night before and alf with full illumination. The 16 trials were arnged as follows: eight in the morning and eight the afternoon; four of each of these eight were receded with a 3-hour period of darkness, and ur with a 3-hour period of light; two of each of ese four followed an overnight period of darkss and two an overnight period of light. An nalysis of variance showed significant variation nly with respect to the 3-hour pretrial light- or dark-adaptation period ($F=5.8$, $P=0.05$). The effects of overnight lighting and time of day were of doubtful significance ($F=3.4$, $P=0.1$, and $F=2.6$, $P>0.1$, respectively). The scores are shown in table 6. Pretrial adaptation to darkness reduced the effectiveness of light attraction.

TABLE 6.—*Comparison of scores* [1] *for light attraction of herring in relation to prior light experience and time of day (experiment 14)*

Time of day	Overnight darkness		Overnight light	
	Dark [2]	Light [2]	Dark [2]	Light [2]
AM	103	90	127	205
	105	153	132	134
PM	100	168	146	193
	155	162	136	170
Mean score	114	143	128	175

[1] Score=sum of numbers of herring counted in the illuminated half of the tank at 30 1-minute intervals. Ten herring were used in each test; maximum possible score=300.

[2] Light condition for 3 hours preceding trials.

Experiment 15. This experiment was done later in the year than experiment 14 at the higher temperature range of 15 to 17.5° C. No allowance was made for any previous light experience of the fish prior to a 6-hour light or dark period of adaptation before each trial. The experiment also included the additional variable of oxygen concentration and was actually a part of experiment 12. The mean score for 15 trials preceded by a 6-hour dark period was 122; that for 15 trials preceded by a 6-hour light period was 136. The difference between them was not significant ($F=1.48$, $P>0.2$). Apparently, previous adaptation to light or dark makes little difference in the response of herring to light at high temperature.

Experiment 16. The pretrial adaptation of herring to light produced the strongest positive response when the trials were made at low temperature. The most marked attraction in experiment 14 occurred during the first minute of the trial: the scores during the first minute differed by 57 percent; the total scores differed by only 25 percent. This fact suggests that light or dark adaptation affects the initial attraction to light more than it affects the tendency for the light to hold the fish.

Although the total scores at high temperature in experiment 15 did not differ significantly between light- and dark-adapted herring, the first minute scores were somewhat (though not significantly) higher for light-adapted herring. Experiment 16

demonstrated that the first minute scores for light-adapted herring were, in fact, significantly higher even at high temperature than those for dark-adapted herring. Four trials at 15 to 17.5° C. were made each day for 4 days; each trial was preceded by a 1-hour period of light or darkness. Counts of the fish were made at 15, 30, 45, and 60 seconds after the attracting light was turned on. The end of the tank illuminated, left or right, was alternated with each trial. The mean score for the fish adapted to light for 1 hour was significantly higher ($F=32.7$, $P<0.01$) than the mean score for the dark-adapted fish (table 7). A significant bias for one side of the tank also was apparent in this experiment. Such a bias sometimes occurred for unknown reasons and made left-right alternation of the illuminated side of the tank a necessary part of the procedure in all experiments.

This experiment showed that previous adaptation to light increases the initial attraction of the herring to light regardless of temperature; on the other hand, the holding effect of the light was weakened at high temperature regardless of the prior adaptation.

TABLE 7.—*Comparison of scores*[1] *for light attraction of herring during first minute of exposure, in relation to prior light experience (experiment 16)*

Location of light	Herring	
	Light adapted	Dark adapted
Left	31	36
	37	33
	29	25
	34	21
Right	23	5
	30	5
	30	10
	33	7
Mean score	31	18

[1] Score = sum of numbers of herring counted in the illuminated half of the tank at four 15-second intervals. Ten herring were used in each test; maximum possible score = 40.

ANALYSIS OF BEHAVIOR IN RESPONSE TO LIGHT

The attraction of herring to artificial lights is a composite behavior pattern made up of two general categories of responses: those that draw the fish toward the light and those that hold the fish under the light's influence. The initial attraction seems to be a (usually) positive telotaxis, defined by Frankel and Gunn (1961) as direct attainment of orientation, without deviations, to a source of stimulus as if it were a goal. This response is stronger in some individuals than in others and in a few may even be negative (away from the light).

The holding power of the light, on the other hand, is determined by several, often dissimilar, responses of the fish. One of these is the dorsal light reaction discussed earlier; it holds the fish near the light by interfering with normal swimming movements which would lead to escape. Another is photokinesis, where general activity and swimming speed increase with increasing light intensity; this response works in opposition to the dorsal light reaction, tending to cause dispersal. Adaptation and fatigue probably accompany continued exposure to the light and may weaken both of the other reactions. Finally, there is the startling or shock effect of sudden changes in light intensity, which may repel the fish, as if by fright.

The response of fish to light is determined by the way in which conditions influence these behavioral components. Some of these reactions can be summarized as follows: Temperature affects primarily the degree to which the fish are held under the influence of the light, probably through its effect on their activity; higher temperature increases general activity, which in turn tends to cause dispersal. The position of the light above or below the surface also affects the holding power of the light. Herring are accustomed naturally to light rays directed downward from the surface, and light from a source below the surface is likely to produce orientation which interferes with normal swimming and escape from the lighted zone. Previous adaptation affects primarily the initial attraction to the light, which is stronger in light-adapted fish than in dark-adapted fish.

An attempt to measure the startle effect of light indicated that whenever the attraction or holding power of the light was strong, the startle effect was less pronounced than when the attracting or holding power was weak. The startle effect was measured by the ratio of the number of fish in either side of the tank before the light was turned on to the number present immediately afterwards. A correlation of -0.957 was found between these ratios and the scores for 10 experiments selected

include those circumstances favorable to light traction and those unfavorable.

The difference in response to light shown by dividual fish and by fish in groups under other- se similar conditions may be another significant pect of behavior. The data from experiment 1, which the responses of 90 individual herring to ght were tested at three different temperatures, d from experiment 6, in which the responses of herring were tested in groups of 10 at the same ree temperatures are an example. If the fish sted individually are combined arbitrarily into ree groups of 10 for each temperature, and the ean score for each group is expressed as a percent- e of the maximum possible score, measures of riance among the groups can be calculated. Simi- rly, the variance among the scores, expressed as a rcentage of the maximum possible score, can be lculated for the actual groups of 10 fish observed experiment 6. A comparison shows that the riance among the scores of the actual groups of fish is significantly greater than the variance nong the scores of the arbitrarily created groups fish tested individually. In fact, the variance nong the scores of the actual groups is not sig- ficantly different from the variance among the ores of individuals. These facts imply that the llective response of 10 herring in a group is not mply an average of their individual responses. stead, the collective response seems to reflect the dividual responses of only one or two fish in the roup.

To explain the apparent lack of thermal in- nence on fish individually in contrast to the gnificant thermal influence on groups, I suggest e following hypothesis. Most herring are only ebly influenced by temperature in their response light. The preponderance of fish in this category uses the average response to appear uninfluenced temperature when each fish responds as an indi- dual, even though a few individuals may be rongly influenced. When the fish are in groups, wever, the weakly influenced majority respond t so much to the stimulus itself as to the strongly fluenced minority, whose behavior dominates e group. I believe that in this interaction lies e significance of the school in fish behavior: e interaction provides to the group a sensitivity d an ability not possessed by individuals to act in an unequivocal manner to a situation.

RESPONSES OF HERRING TO LIGHT AND THEIR APPLICATION IN THE FISHERY

Without doubt attraction to artificial lights at night is a significant behavioral response of herring, and it is potentially useful in the herring fishery. The question is: Under what conditions is this response brought out most strongly and what tactics in using lights can be most effectively employed?

Most of the evidence indicates that a submerged light is more effective than one above the surface. One reason is that the entire output of the underwater light is used, whereas a large portion of the light from above the water is reflected from the surface. The submerged light is also more uniform: the rays do not flicker from the effect of a ruffled surface. Moreover, the submerged light has an improved attracting effect which is independent of its greater efficiency. A submerged light which produced only 1/10 to 1/1,000 the underwater illumination of a light above an unruffled surface proved to be the more effective in laboratory experiments. Because of refraction, the rays from a light above the surface project sharply downward, even at some distance from the light source. It may be that the direction of the rays in relation to the position of the fish are important, and that rays from above the surface approaching the vertical tend to repel herring. The light from the sun, sky, or a bright moon would be of this nature; all of these light sources tend to keep the herring from the surface and may be the cause of the characteristic diurnal vertical migrations of herring.

Evidence from my experiments and also from other studies shows that the brightest lights are not necessarily the most effective for attracting herring. Although a brighter light will have a greater range and can be seen by fish at a greater distance, the illumination within a certain radius may exceed the optimum and tend to repel the fish even if they are attracted up to that radius. To obtain maximum range while still attracting nearby fish, certain manipulations of the light have been used effectively. The simplest method is to dim the light gradually (Gauthier, in press; Kurc, in press; Ström, in press). Another scheme was described by Sasaki (1959): A series of lights of optimum brilliance extend some distance from

the fishing operation. The outermost light is turned on for a time until a substantial number of fish are attracted. This light is then extinguished, and another somewhat closer to the fishing operation is illuminated. Each light in the series is lighted and extinguished in sequence, attracting in turn the fish gathered about the preceding one.

Besides the properties of the light itself, certain factors of the environment govern the effectiveness of the light, especially in relation to the time of day or time of year it is used. Kawamoto (1959) showed that in some species of fish the light-seeking tendency was stronger in the daytime than at night. Tamura (1959), discussing this phenomenon and certain physiological changes in the eye of the fish when adapted from light to darkness, suggested "this may be one of the fundamental reasons why fishing with the use of light is usually more effective before than after midnight." The results of my own experiments with herring show a greater attraction to light of light-adapted fish, especially the initial attraction. All of these observations suggest that fishing with a light would be most effective shortly after dusk.

I can find no reference to the effect of temperature on the response of herring to light except as it relates to their passage through the thermocline; there are records, however, indicating that temperature does affect the response to light of other species of fish. Andrews (1946) showed that the positive phototaxis of suckers (*Catastomus*) was weakened at high temperature; Grubišić (1962) stated that the attraction of sardines (*Sardina pilchardus*) to light was weaker in the summertime than at other seasons and that this weakness was "more evident when the summers are more than normally hot."

Because the attraction of herring to light seems also to be weakened at high temperature, success in fishing for them with artificial lights might well depend in part on the season of the year and the temperature characteristics of particular localities. Moreover, temperature seems not only to affect directly the attraction to light, but also to modify the effects of light position and previous adaptation to light or darkness.

My purpose in the experiments involving temperature was limited to finding out whether temperature had any effect at all. Obviously, it did, but the critical values of both experimental and adaptation temperatures need yet to be defined. It is possible that the temperature preferendum described elsewhere (Stickney, in press) represents the critical point above which the light response weakens.

The use of lights in the herring fishery of the Canadian and United States Atlantic Coast has been in disfavor for some time and is even illegal in many places. Even where it is still legal, it is a method of little importance probably because fishermen believe that lights frighten the herring away (Scattergood and Tibbo, 1959). Fishing at night is carried on with as little light showing as possible. Because above-water lights, excessively bright lights, and lights suddenly flashed on or moved about do apparently frighten herring, the caution used in showing lights is probably justified. On the other hand, practical experience and biological evidence indicate that lights properly used under some circumstances can attract herring effectively. It would seem that artificial lights used in accordance with what is known about herring behavior would provide an extremely useful method for controlling the herring schools so that they would be in locations most conducive to setting purse seines or stop seines around them.

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ARIATIONS IN MARINE ZOOPLANKTON FROM A SINGLE LOCALITY IN HAWAIIAN WATERS

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ABSTRACT

Data on marine zooplankton and hydrography were tained off Oahu, Hawaii, at monthly intervals from ne 1957 through December 1958.

Samples collected at 3-hour intervals for 48 hours June 1957 were examined for diel variation. Volumes zooplankton exhibited the expected sinusoidal vari-ion during the first 24 hours, but not during the cond. High volumes during the second morning re attributed to the presence of an unidentified atom that retarded drainage of moisture during de-rmination of volumes of zooplankton. Variations in undance were sinusoidal for Ostracoda, Euphausi-ea, Pteropoda, and fish larvae. Similar variations in rface temperature and depth from the surface to e top of the thermocline were attributed to solar heating and internal waves, respectively.

The 19 monthly samples showed correlations between volumes of zooplankton and salinities and between volumes of zooplankton and depth to the top of the thermocline. The 19 months were divided into nine successive periods, each with a temperature-salinity curve differing from that of the preceding and following periods. Volumes of zooplankton and the abundance of Siphonophora, Chaetognatha, Euphausiacea, decapod Crustacea, and Pteropoda increased when portions of the temperature-salinity curves greater than 35.0‰ increased during the nine periods; and, conversely, the volumes of zooplankton and the abundance of these groups of zooplankters decreased as the amount of water with salinity greater than 35.0‰ decreased.

Once every month from June 1957 through ecember 1958, members of the Bureau of Com-ercial Fisheries Biological Laboratory, Honolu-, collected hydrographic and meteorological ata from a station located at lat. 21°10.3′ N., long. 58°19.0′ W. for the Island Observatory Project f the International Geophysical Year Oceano-raphic Program (Scripps Institution of Ocean-graphy, 1965). This position, referred to as the GY station, is about 32 km. southwest of Barbers oint, Oahu, where the depth of the water is about 000 m.

Samples of zooplankton were also collected at ne IGY station for studies of variations in the anding crop and composition of marine zoo-lankton in relation to environmental factors at single locality in Hawaiian waters. The results owed that volumes of zooplankton were high in aters of high surface and subsurface salinities.

METHODS

The samples of zooplankton were collected with net having a mouth diameter of 1 m.; a flowmeter was mounted in the center of the opening. The body of the net was constructed of synthetic fiber of 0.656 mm. aperture width; the rear section, including the cod end, was made of synthetic fiber of 0.308 mm. aperture width. Detailed descriptions of the construction of the net and the method of making the tow have been presented by King and Demond (1953).

The nets were towed obliquely from the surface to a depth of 60 m. and back in one-half hour. In June 1957, such hauls were made at 3-hour intervals over a 48-hour period to measure diel variations. In the succeeding months, four half-hour hauls were made each time the station was occupied: two successive daylight hauls starting at about 1600 l.s.t. (local standard time) and two successive night hauls between 2100 and 0300 l.s.t.

The methods of processing and determining the volumes of the samples of zooplankton have been described by King and Hida (1954, 1957a). Counts of various groups of plankters were made on the night samples.

For the counts, an aliquot of a sample was first placed in a counting cell (a 15 by 20 by 1.5-cm.

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plastic dish) which had 300 subdivisions ruled into its bottom. The organisms in 40 randomly selected squares were identified and counted under a dissecting microscope. The estimated number of a group of organisms in 1,000 m.^{3} of water was calculated by the following formula (modified from King and Demond, 1953):

$$E=\frac{CA}{fanW}1{,}000$$

where E=number of organisms per 1,000 m.^{3} of water
C=counted number of organisms
A=area of counting cell (300 cm.^{2})
f=fraction of total sample in the counting cell
a=area of square (1 cm.^{2})
n=number of squares counted (40)
W=cubic meters of water strained by net

Usually, on each visit to the IGY station, two hydrographic casts were made, one during the highest tide and the other during the lowest tide. Ordinarily, each cast was from 0 to 500 m. depth and consisted of 12 Nansen bottles, but on some occasions the casts were deeper. Temperature and salinity data were obtained with each cast, and with a few exceptions, oxygen and inorganic phosphate were also measured. Additional temperature data were obtained with bucket thermometers and bathythermographs.

Salinity determinations were made by a modification of the Knudsen method (Van Landingham, 1957); inorganic phosphate determinations were made with a Beckman [1] spectrophotometer.

Temperature, salinity, phosphate, and oxygen values used in the study were averaged as follows:

Surface value: average of measurements obtained at water surface during high tide and low tide.

0 to 60 m. value: average of measurements at depths of 0, 10, 20, 30, 40, 50, and 60 m. during high tide and low tide.

200 to 300 m. value: average of values at 15-unit increments between the 400 and 300 thermosteric anomaly surfaces on a temperature-salinity plot. These two anomaly surfaces represented approximately 200 and 300 m., respectively.

[1] Trade names referred to in this publication do not imply endorsement of commercial products.

Vertical temperature distribution: isotherms were contoured on the basis of the average temperatures at the following depths: 0, 9.2, 15.2, 30.5, 45.8, 61.0, 76.2, 91.5, 100.6, 122.0, 149.4, 152.5, 183.0, 199.8, 213.5, 244.0, and 274.5 m. Readings were limited to a maximum of five bathythermograms per month.

DIEL VARIATIONS

In central Pacific waters, diel variation in volumes of zooplankton and in abundance of certain zooplankton has been shown to vary as the curve of the sine function (King and Hida, 1954; Legand, 1958; Nakamura, 1967); the peak equated to midnight. The volumes and abundance of zooplankters determined from samples obtained at 3-hour intervals from June 21 to 23, 1957, were examined for similar variations. Temperatures and depths to the top of the thermocline for this period were also examined for diel variations.

VOLUMES OF ZOOPLANKTON

The volumes of zooplankton obtained for the 48-hour series ranged from a low of 13 cc./1,000 m.^{3} of water strained to a high of 40 cc./1,000 m.^{3}, with a mean of 26 cc./1,000 m.^{3} (fig. 1). The volumes of the samples obtained during the night were greater than those of the samples collected by daylight; the night to day ratio was 1.3 : 1. The greater abundance of zooplankton in darkness has been attributed by investigators to some combination of an upward migration by the zooplankters and an increased avoidance of the net by some organisms in daylight (King and Hida, 1954, 1957a; Fleminger and Clutter, 1965; Brinton, 1967).

The volumes from the 48-hour series appeared to conform approximately to a sinusoid for the first 24-hour period but not for the second. The volumes remained high through the second morning. An unusually large amount of an undetermined species of diatom was present in samples 11, 12, 15, and 16. The greater resistance of these samples to moisture drainage than of those without diatoms resulted in a greater determination of wet volume. This fact may have explained the unusually high volumes in samples 12, 15, and 16. On the other hand, the volume of sample 11 did not appear to be unusual even though it too contained diatoms.

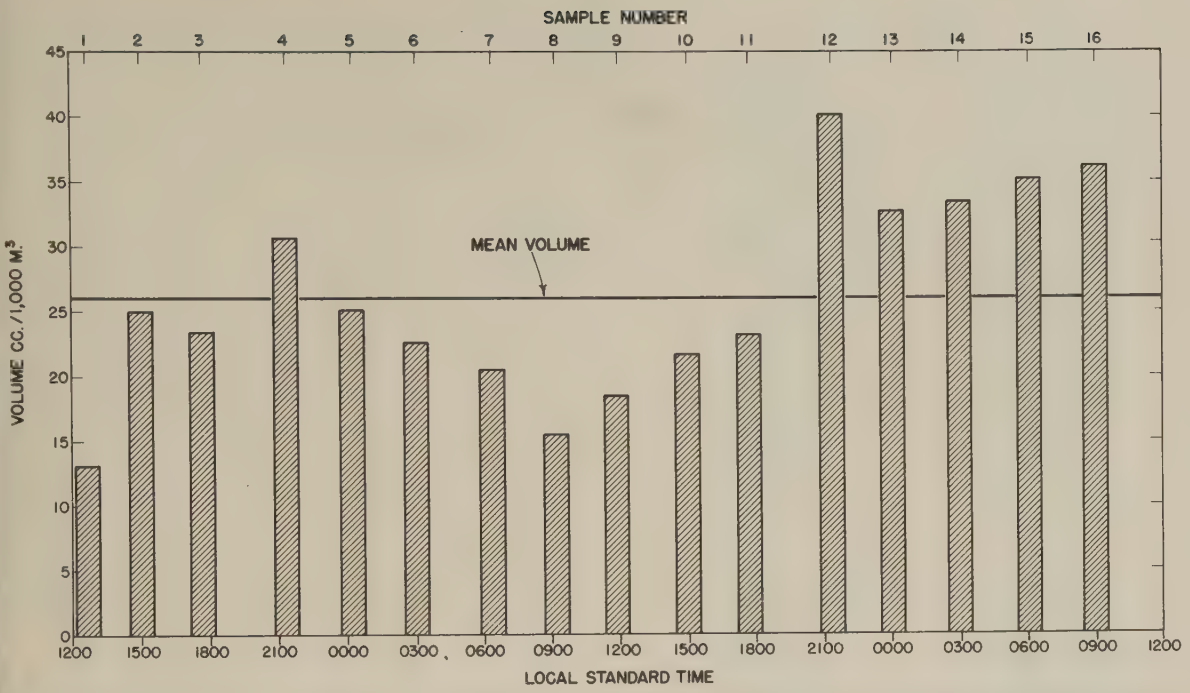

FIGURE 1.—Variations in volumes of zooplankton over a 48-hour period, June 21–23, 1957, at the IGY station. Sunrise during this period was at 0503 and sunset at 1846 hours.

COMPOSITION OF ZOOPLANKTON

Abundance of groups of plankters expressed as verage numbers per 1,000 m.³ of water strained nd as average percentages of total numbers of lankters is summarized in table 1. By far the most umerous organisms in the samples were copepods, hich on the average constituted about 60 percent f all organisms present. Chaetognatha and *Halo-haera viridis*,[2] almost equal in average abun-ance, were the second and third most common rganisms in the samples. Numerically, each aver-ged less than 10 percent of the copepods.

Distinct diel variations, with greater numbers uring darkness, were exhibited by Ostracoda, uphausiacea, Pteropoda, and fish larvae (fig. 2). mphipoda exhibited such a diel variation only uring the second half of the series (fig. 2). In ddition to the aforementioned groups, Annelida Polychaeta) and calanoid Copepoda have been nown previously to exhibit distinct diel variations n Hawaiian waters (Nakamura, 1967). In this udy, these two groups did not show the character-tic peaks of abundance during darkness. Perhaps specific or generic identifications had been made diel fluctuations would have been revealed, for Nakamura (1967) found that the following genera of calanoid copepods were concentrated in the upper waters during darkness: *Pleuromamma*, *Neocalanus*, *Candacia*, *Undinula*, and *Euchaeta*. In the present study abundance of Heteropoda reached a peak during daylight as well as at night.

TABLE 1.—*Average abundance and average percentage composition of various plankters for 16 samples of the 48-hour series*

Plankters	Average abundance	Average composition
	No./1,000 m.³	*Percent*
Halosphaera[1]	1,654	5.6
Foraminifera	775	2.6
Radiolaria	572	1.9
Siphonophora	1,088	3.7
Chaetognatha	1,626	5.5
Annelida	132	.4
Calanoid Copepoda	17,788	59.8
Noncalanoid Copepoda	1,024	3.4
Ostracoda	866	2.9
Euphausiacea	664	2.2
Amphipoda	1,189	4.0
Decapod Crustacea	1,075	3.6
Pteropoda	290	1.0
Heteropoda	147	.5
Gastropod larvae	64	.2
Pelecypoda	50	.2
Thaliacea	51	.2
Appendicularia	422	1.4
Fish larvae	129	.4
Fish eggs	35	.2
Others	82	.3

[1] *Halosphaera viridis*, a phytoplankter, numerous in all samples.

[2] This phytoplankter was present in every sample and was included in all counts.

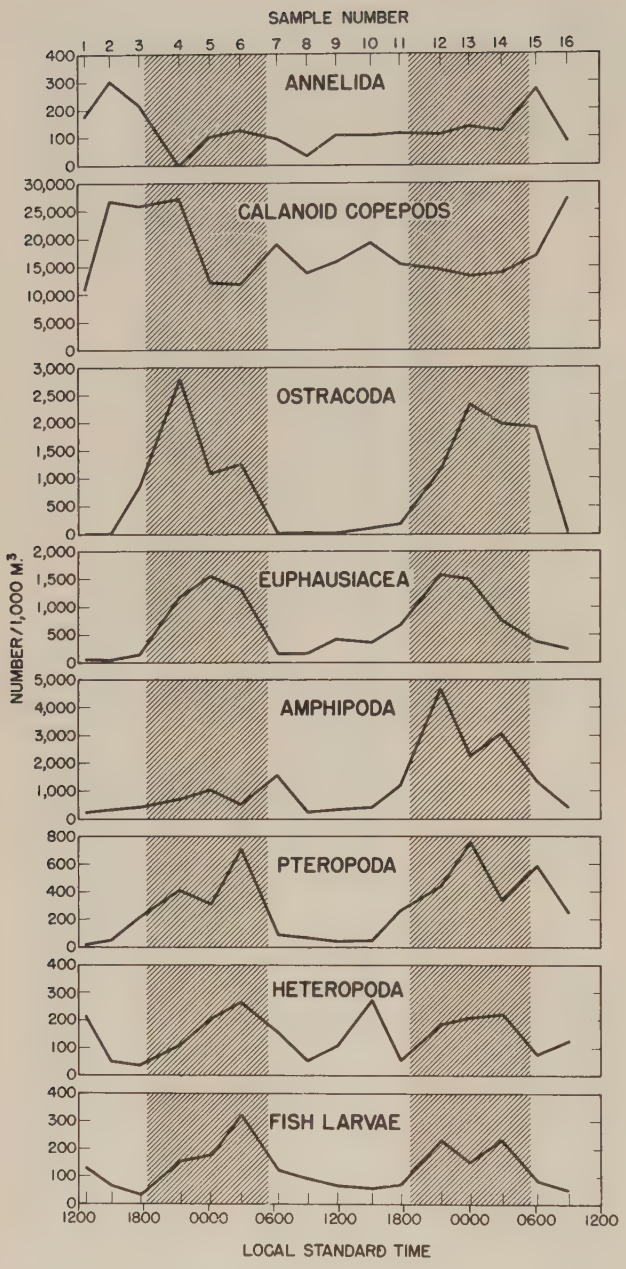

FIGURE 2.—Variation in the abundance of various groups of zooplankters during June 21–23, 1957, at the IGY station.

TEMPERATURE

The diel variation in surface temperature (fig. 3) was attributed to solar heating during the day and cooling at night. A subsurface thermal disturbance was evident between 0400 and 1200 hours, June 22. It was probably caused by advection; however, unusual changes in the volumes of zooplankton did not occur during the thermal disturbance.

DEPTH FROM SURFACE TO TOP OF THERMOCLINE

The sinusoidal variation in the depth from the surface to the top of the thermocline (fig. 3) showed fluctuations probably caused by internal waves. The variations in depth to the top of the thermocline, however, did not appear to influence the abundance or composition of the zooplankton during the 48-hour period. The depths for the hauls of zooplankton in this series ranged from 52 to 65 m. The depth from the surface to the top of the thermocline ranged from 23 to 61 m. Sample 8 was the only one collected entirely within the isothermal layer above the thermocline. The volume of sample 8 was not unusual. Chaetognatha had their least abundance and Pelecypoda their greatest abundance in this sample.

CORRELATIONS BETWEEN ZOOPLANKTON AND PHYSICAL AND CHEMICAL FACTORS

King and Hida (1954, 1957b), in their studies of the distribution and abundance of zooplankton in Hawaiian waters, were unable to show a consistent relation between the standing crop and temperature, surface phosphate, dissolved oxygen, and depth from the surface to the top of the thermocline. Analyses of their data from seven cruises gave one statistically significant correlation ($P<0.05$) between zooplankton and temperature (at 10-m. depth) and one significant correlation ($P<0.01$) between zooplankton and surface phosphate. King and Hida's samples were taken from a large area around the Hawaiian Islands.

Consistently high or low standing crops regardless of changes in the environment (McGary 1955; Seckel, 1955) have been found in certain areas in Hawaiian waters. For example, King and Hida (1954, 1957b) found consistently low volumes of zooplankton from immediately east of the island of Hawaii.

The results of the correlation analyses for the present study, where sampling was confined to one locality, are summarized in table 2. Volumes of zooplankton were examined in relation to the physical and chemical data for the surface, 0 to 60 m. (range in depth of the hauls for zooplankton),

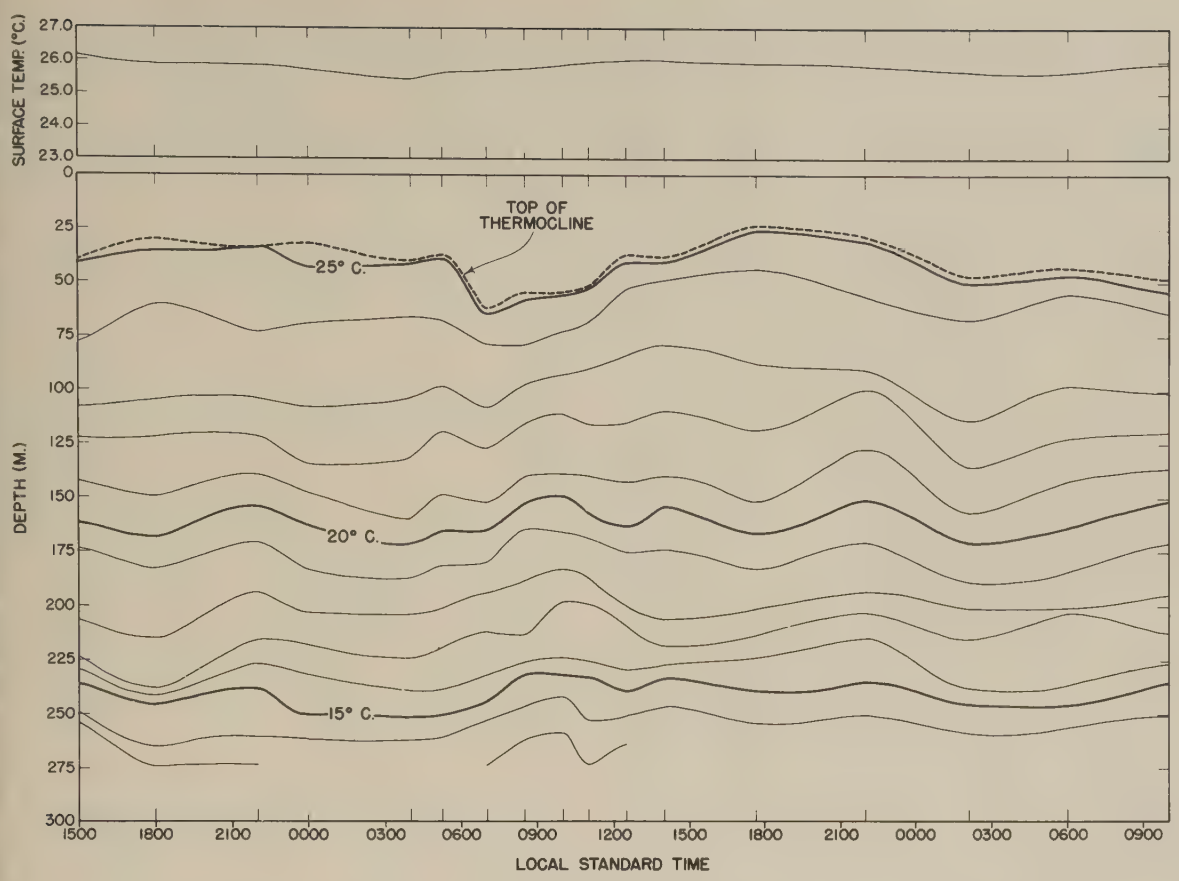

FIGURE 3.—Vertical distribution of temperature during June 21–23, 1957, at the IGY station.

ABLE 2.—*Summary of correlations between volumes of zooplankton and certain physical and chemical environmental factors*

First variate (X_1)	Second variate (X_2)		Degrees of freedom	Correlation coefficient (r)
rface salinity °/₀₀).	Zooplankton volume (cc./1,000 m.³).	Night hauls Day hauls	16 16	0.397 **.655
rface oxygen ml./l).	Zooplankton volume (cc./1,000 m.³).	Night hauls Day hauls	14 14	−.029 .228
rface inorganic hosphate µg.at./l).	Zooplankton volume (cc./1,000 m.³).	Night hauls Day hauls	13 13	−.132 −.227
0 m. salinity °/₀₀).	Zooplankton volume (cc./1,000 m.³).	Night hauls Day hauls	16 16	.464 **.706
0 m. emperature ° C.).	Zooplankton volume (cc./1,000 m.³).	Night hauls Day hauls	16 16	.025 −.236
–300 m. alinity (°/₀₀).	Zooplankton volume (cc./1,000 m.³).	Night hauls Day hauls	16 16	*.507 .455
pth to top of hermocline m).	Zooplankton volume (cc./1,000 m.³).	Night hauls Day hauls	16 16	*−.524 *−.544

Significant at 5-percent level.
*Significant at 1-percent level.

and about 200 to 300 m., and also the depth from the surface to the top of the thermocline. Changes in volumes of zooplankton and in physical and chemical factors of the environment during the 19 months are illustrated in figures 4, 5, and 6. Surface values are given in table 3.

Except for June 1957 and October 1958, the volumes of zooplankton obtained at night were greater than those collected by day (fig. 4). The ratio of night to day volumes ranged from 0.9 : 1 to 3.3 : 1 and averaged 1.8 : 1.

Volumes of zooplankton showed close correlations with salinities and depths of the isothermal layer but not with other environmental factors. Positive correlations were significant at either the 5 percent or 1 percent probabilities between volumes of zooplankton for day hauls and salinities at the surface and at 0 to 60 m., and for night hauls and salinities at 200 to 300 m. (table 2). Correlations between volumes of zooplankton for night hauls and salinities at 0 to 60 m. and for day hauls and salinities at 200 to 300 m. were very close

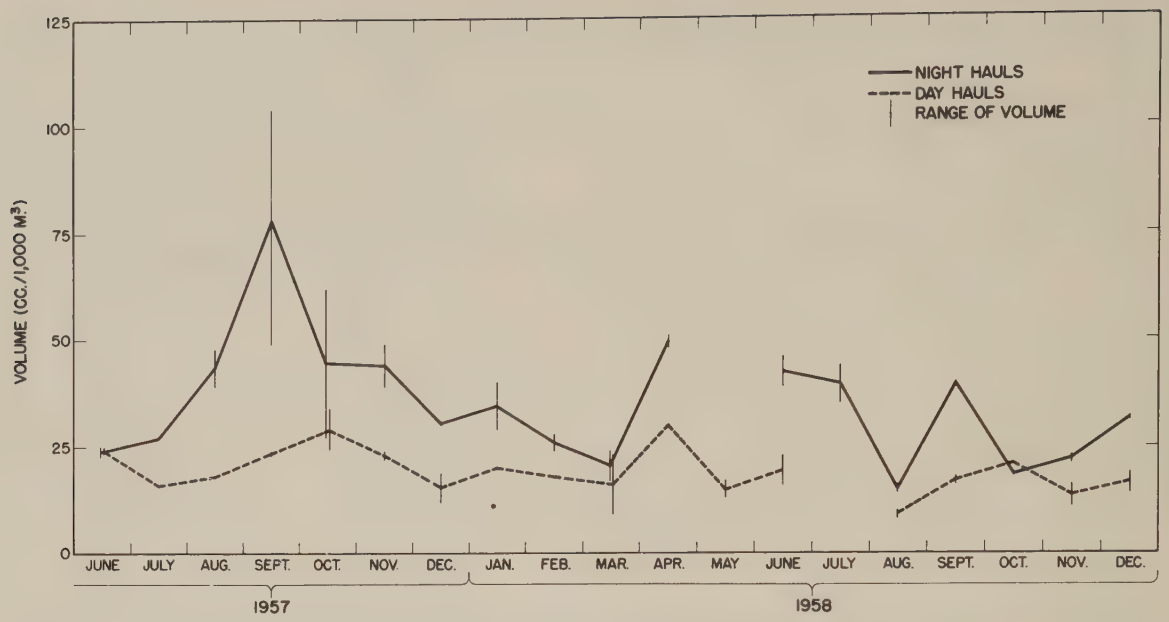

FIGURE 4.—Monthly variations in volumes of zooplankton collected by night and by day at the IGY station from June 1957 to December 1958.

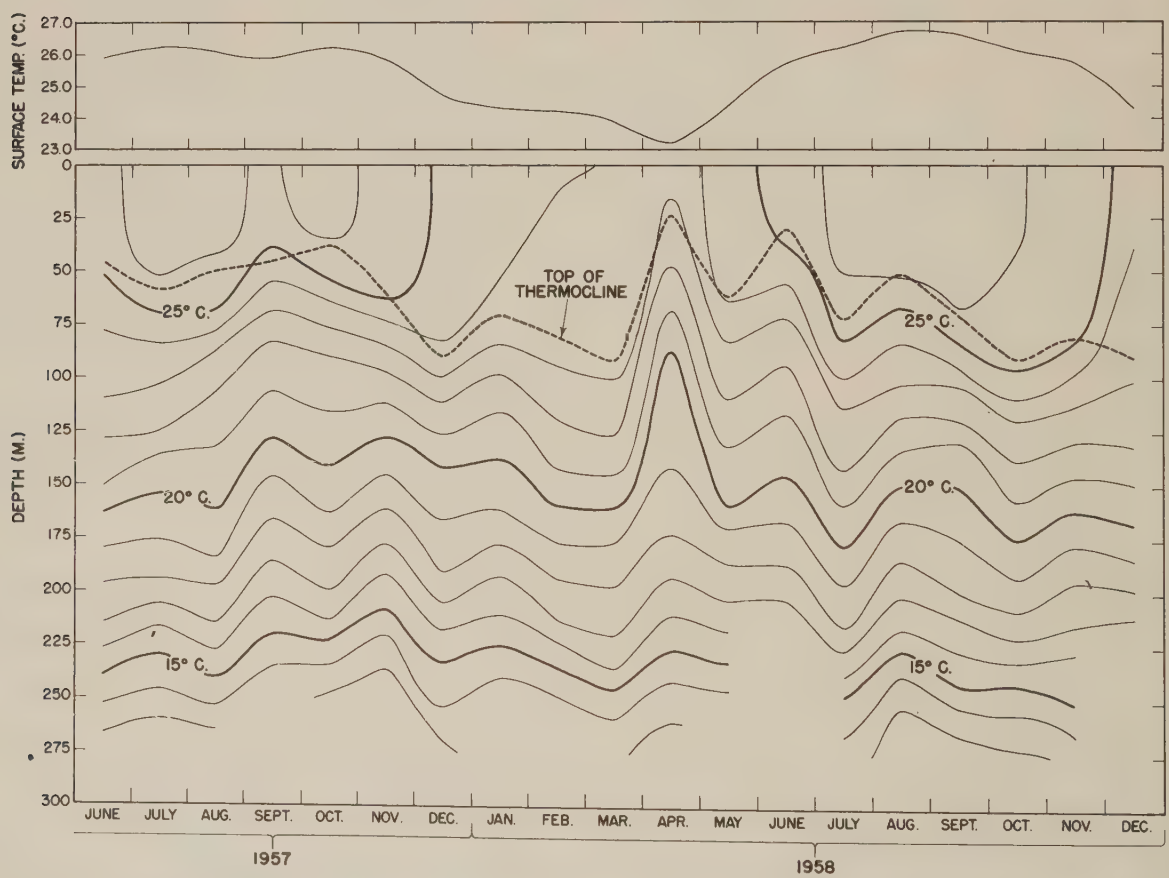

FIGURE 5.—Monthly vertical distribution of temperature at the IGY station from June 1957 to December 1958.

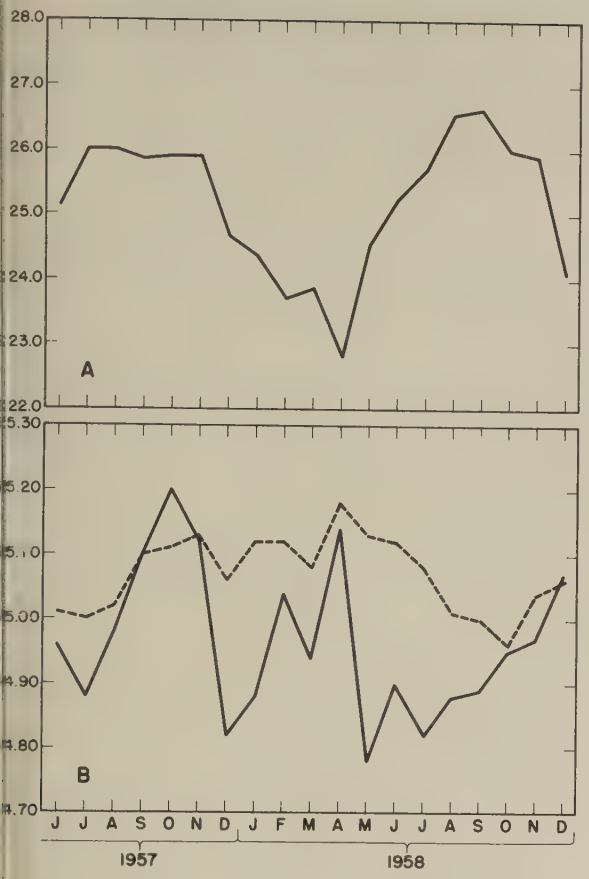

FIGURE 6.—Monthly variation in temperature and salinity at the IGY station from June 1957 to December 1958. A. Mean 0 to 60 m. temperatures. B. Mean 0 to 60 m. salinities (solid line) and mean 200 to 300 m. salinities (dashed line).

significance at the 5 percent probability (for = 0.05 and d.f. = 16, r = 0.468). Negative correations were significant between volumes of zooankton for both night and day hauls and depths om the surface to the top of the thermocline. ither temperature, oxygen, nor inorganic phosate was correlated with volumes of zooplankton. We believe the significant relations between zooankton and salinity and between zooplankton d the thickness of the isothermal layer resulted om the advection of different types of water into Hawaiian area. The biomass of zooplankton s higher in waters of high salinity.

ZOOPLANKTON AND TEMPERATURE-SALINITY CURVES

Seckel (1962) indicated that the Hawaiian Isds are located near the northern boundary of transition zone between two major types of

TABLE 3.—*Monthly values of surface salinity, inorganic phosphate, and oxygen during low and high tides at the IGY station*

Month	Salinity °/₀₀		Phosphate μg.at./l		Oxygen ml./l	
	Low tide	High tide	Low tide	High tide	Low tide	High tide
1957						
June	34.97	34.97	0.22	0.20	4.29	4.32
July	34.87	34.88	.29	.24	4.47	4.46
August	34.96	34.96	.20	.22	4.79	4.78
September	35.07	35.12	.13	.16	----	4.45
October	35.19	35.16	.10	.16	4.53	4.51
November	35.12	35.12	.11	.16	4.78	4.64
December	34.72	34.81	3.65	----	4.58	4.56
1958						
January	34.81	34.85	.12	.13	4.79	4.69
February	35.03	35.05	.22	.20	4.85	4.84
March	34.94	34.96	.64	1.60	4.60	4.66
April	35.10	35.07	----	----	----	----
May	34.80	34.77	.06	.62	4.55	4.62
June	34.90	34.82	----	----	4.08	4.18
July	34.81	34.80	.49	.70	4.77	4.80
August	34.91	34.89	.39	.22	4.43	4.55
September	34.86	34.87	----	----	4.55	4.64
October	34.94	34.96	.21	.23	----	4.40
November	34.96	34.94	.11	.10	----	----
December	34.94	35.05	----	.35	----	4.64

surface water: (1) the high-salinity (surface values >35.0‰) North Pacific Central Water, and (2) the low-salinity (surface values <34.2‰) North Pacific Equatorial Water. These water types corresponded approximately with the subsurface water masses as defined by Sverdrup, Johnson, and Fleming (1942). Seckel (1962) classified the California Current Extension, which forms the core of the transition zone, as a third type. He showed that the boundaries of these water types shifted seasonally and affected the type of water to be found near Oahu.

Our data were analyzed from the standpoint of advection of different types of water as indicated by changes in the temperature and salinity during the 19 months of observation. The data were divided into the following nine chronological periods (fig. 7) on the basis of the similarity in the temperature-salinity (T-S) curves for successive months: June to July 1957, August 1957, September to November 1957, December 1957 to March 1958, April 1958, May 1958, June to July 1958, August to November 1958, and December 1958. Each period had temperature and salinity characteristics that were different from the preceding and succeeding periods. The average monthly (0–60 m.) temperatures, the average monthly salinities (0–60 m. and 200–300 m.), and the average depth from the surface to the top of the thermocline for the nine periods are illustrated in figure 8.

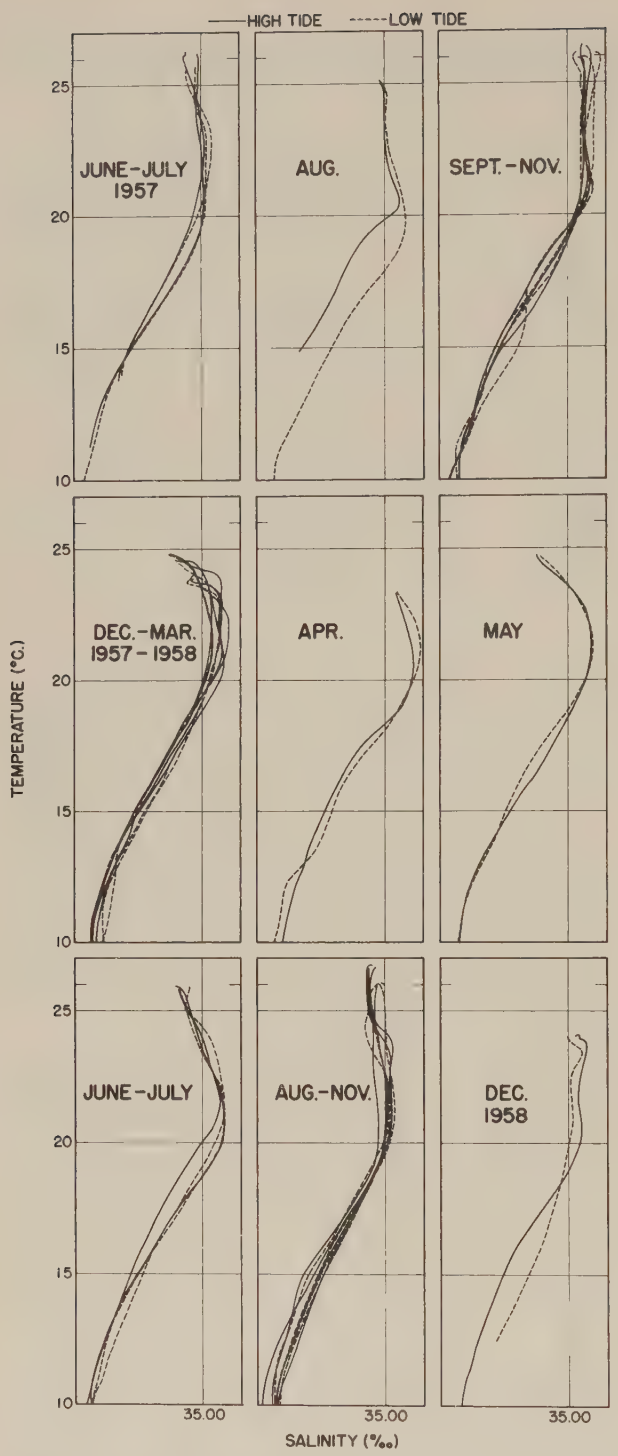

FIGURE 7.—Monthly temperature-salinity relation at highest high tide and lowest low tide at the IGY station by periods.

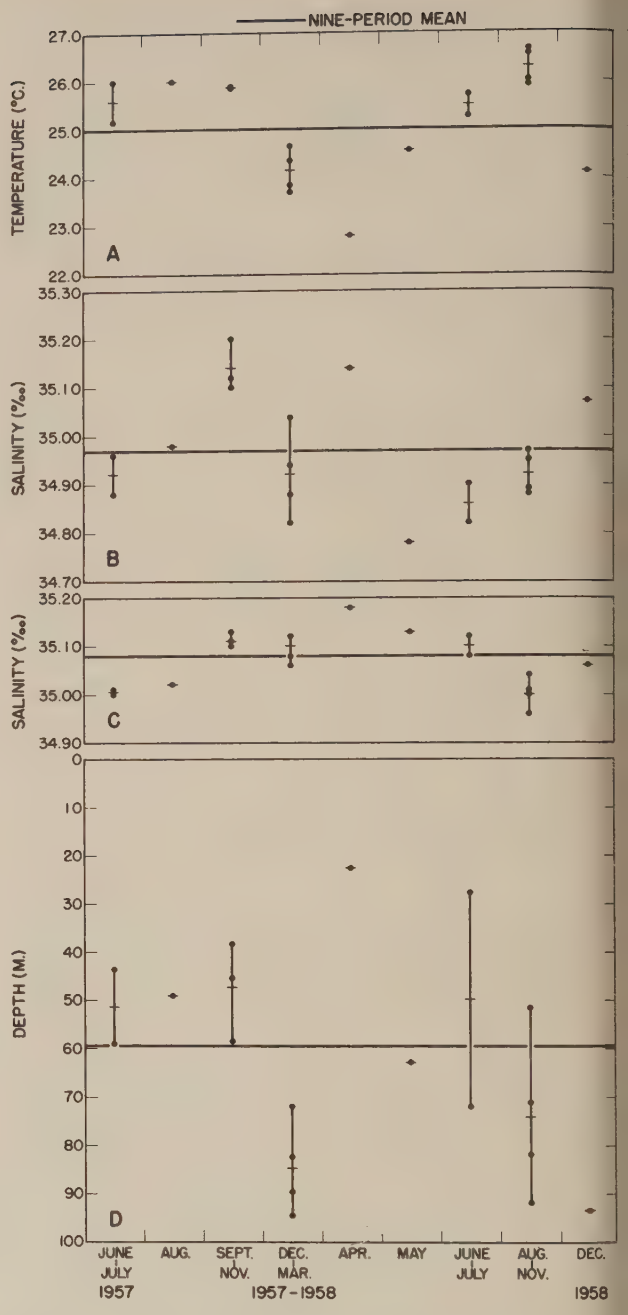

FIGURE 8.—Physical and chemical characteristics of the nine periods. A. Average 0 to 60 m. temperatures. B. Average 0 to 60 m. salinities. C. Average 200 to 300 m. salinities. D. Average depth from the surface to top of thermocline.

TABLE 4.—*Average abundance (No./1,000 m.³) of various plankters from samples taken at night at the IGY station*

Plankters	Period and (in parentheses) number of samples								
	June, July 1957 (2)	Aug. 1957 (1)	Sept., Oct., Nov. 1957 (3)	Dec. 1957, Jan., Feb., Mar. 1958 (4)	Apr. 1958 (1)	June, July 1958 (2)	Aug., Sept., Oct., Nov. 1958 (4)	Dec. 1958 (1)	Eight-period mean (8)
osphaera [1]	5,392	1,771	3,047	3,569	5,284	1,582	2,400	5,102	3,518
aminifera	660	551	283	286	1,308	94	274	559	502
diolaria	204	394	158	156	366	38	142	298	220
nonophora	2,196	3,543	5,943	3,055	4,185	6,137	3,723	4,358	4,142
etognatha	1,346	2,834	2,955	1,259	4,813	2,420	2,346	3,128	2,638
elida	184	157	238	188	366	357	128	410	254
anoid Copepoda	12,762	38,733	32,069	18,704	30,395	20,078	13,489	24,916	23,893
n-calanoid Copepoda	1,359	2,362	2,301	1,192	4,028	1,796	1,898	2,905	2,230
racoda	1,974	2,559	2,633	3,515	6,069	607	550	1,937	2,480
phausiacea	1,338	2,440	4,541	1,673	3,139	1,662	1,893	1,788	2,309
phipoda	958	905	526	401	942	869	548	521	709
apod Crustacea	2,120	3,976	4,460	1,842	3,768	3,060	3,331	5,028	3,448
ropoda	486	945	1,361	546	1,360	446	1,049	1,378	946
eropoda	247	79	394	38	52	68	118	----------	124
tropod larvae	50	197	174	33	105	138	136	298	141
ecypoda	50	----------	74	177	----------	44	132	223	88
uliacea	11	157	202	464	1,308	668	146	372	416
oendicularia	135	157	851	720	3,191	216	255	1,639	896
n larvae	234	236	269	292	366	692	171	----------	282
h eggs	96	79	31	90	314	25	21	112	96

[1] *Halosphaera viridis*, a phytoplankter.

The physical, chemical, and biological characteristics of each of the nine periods are discussed below. For the discussion the averages for each period are considered high or low relative to the overall average for the nine periods. A night sample of zooplankton was not taken in May 1958; thus, the counts of zooplankton for night collections are divided into eight rather than nine periods (table 4).

JUNE TO JULY 1957

This period was characterized by relatively high temperatures, low salinities, and a shallow isothermal layer. The average 0 to 60 m. temperature was .6° C. The 0 to 60 m. and 200 to 300 m. average linities were 34.92‰ and 35.00‰, respectively, mpared to the nine-period means of 34.97‰ and .08‰. The average depth to the top of the thermocline was 51.4 m. (fig. 8).

The average volume of zooplankton for day auls equaled the nine-period mean of 20 cc./000 m.³ (fig. 9); the average night volume of 25 ./1,000 m.³ was lower, however, than the eight-eriod mean of 37 cc./1,000 m.³ Most of the counts f groups of organisms were low (table 4); *Halo-haera*, Foraminifera, Amphipoda, and Heteropoda were exceptions. The abundance of calanoid opepoda, which numerically make up about 59 ercent of the total standing crop of zooplankton, as very low during this period.

AUGUST 1957

August 1957 appeared to be a transition period (fig. 7). The 0 to 60 m. salinity increased from 34.92‰ to 34.98‰, and the 200 to 300 m. salinity increased slightly from 35.00‰ to 35.02‰. The 0 to 60 m. temperature (26.0° C.) also increased. The depth of the isothermal layer (49.1 m.) decreased from the previous period.

The volume of zooplankton for the day hauls (18 cc./1,000 m.³) for this period was slightly less than the average for June to July 1957; however, the night volume (44 cc./1,000 m.³) showed a substantial increase. Radiolaria and calanoid Copepoda were more abundant in August 1957 than in any other period.

SEPTEMBER TO NOVEMBER 1957

Temperature and depth of the isothermal layer for this period were lower; salinities were higher than in the previous period. The average 0 to 60 m. temperature was 25.9° C. The depth to the top of the thermocline was 47.4 m. The 0 to 60 and 200 to 300 m. salinities were 35.14‰ and 35.11‰, respectively.

The average volumes and counts of zooplankton were high. Volumes for day (25 cc./1,000 m.³) and night (56 cc./1,000 m.³) samples were both higher than the corresponding averages (20 cc./1,000 m.³ and 37 cc./1,000 m.³) for all periods. Euphausiacea and Heteropoda were more abundant in this period than in any other.

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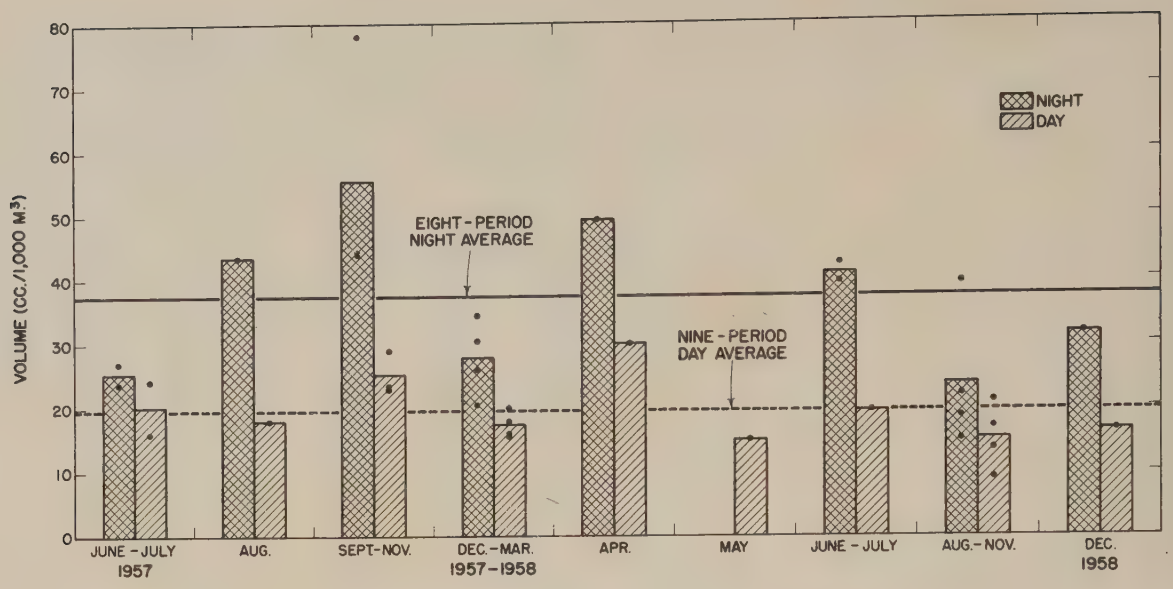

FIGURE 9.—Average volumes of zooplankton during nine periods at the IGY station.

DECEMBER 1957 TO MARCH 1958

Monthly changes of the measured properties from July to November 1957 were gradual; the change from November to December 1957, however, was abrupt. The 0 to 60 m. temperature dropped from an average of 25.9° C. in November 1957 to 24.6° C. in December 1957 (fig. 6A) and remained low, averaging 24.1° C. for December 1957 to March 1958 (fig. 8A). The monthly 0 to 60 m. salinity likewise changed considerably, dropping from 35.12‰ in November to 34.82‰ in December (fig. 6B). The December 1957 to March 1958 average was 34.92‰ (fig. 8B).

The 200 to 300 m. salinity (35.10‰) changed slightly (fig. 8C), but the depth to the top of the thermocline showed a considerable deepening from an average of 47.4 m. during September to November 1957 to 84.6 m. (fig. 8D) for this period.

The volumes of zooplankton declined markedly from the preceding period. The night volume dropped from an average of 56 cc./1,000 m.³ in September to November 1957 to 28 cc./1,000 m.³ The day volumes of zooplankton declined from 25 cc./1,000 m.³ to 17 cc./1,000 m.³ (fig. 9). Except for *Halosphaera*, Ostracoda, Pelecypoda, and Thaliacea the abundance of plankters was relatively low during this period.

APRIL 1958

Maximum and minimum values were recorded for the physical and chemical properties during April 1958 (figs. 6 and 8). The 0 to 60 m. temperature (22.8° C.) was the lowest recorded during the 19 months. The 0 to 60 m. salinity (35.14‰) equaled the September to November 1957 average, the highest average for the nine periods. The 200 to 300 m. salinity (35.18‰) was also the highest for the nine periods. The isothermal layer during this period was the shallowest (22.6 m.) of the nine periods.

The zooplankton showed marked differences from the preceding period. The day and night volumes of 30 cc./1,000 m.³ and 50 cc./1,000 m.³ for April were much higher than those for December 1957 to March 1958. With the exception of Pelecypoda, all of the organisms were more numerous than in the preceding period.

MAY 1958

In May the physical and chemical characteristics of the water differed markedly from those of April 1958. The 0 to 60 m. temperature increased from the low of 22.8° C. in April to 24.6° C. in May. The most important change, however, was in the 0 to 60 m. salinity, which decreased from 35.14‰ in April, the highest for the nine periods, to 34.78‰ in May, the lowest for the nine periods. The 200 to 300 m. salinity decreased slightly from 35.18‰ in April to 35.13‰ in May. These differences suggest that the major change from April to May was in the upper waters. The depth to the top of the thermocline (62.8 m.) was slightly greater than the nine-period mean (59.4 m.).

The average volume of zooplankton for the day uls was 15 cc./1,000 m.^{3}, lower than that for any revious period.

JUNE TO JULY 1958

Except for a continued rise in temperature and shallower isothermal layer, the changes during iis period were not very great. The average 0 to m. temperature was 25.5° C. The average 0 to m. salinity increased to 34.86‰. The average 0 to 300 m. salinity declined further to 35.10‰. he average depth to the top of the thermocline as 49.8 m.

The night volumes of zooplankton for June to ly averaged 41 cc./1,000 m.^{3} as compared to the ght-period average of 37 cc./1,000 m.^{3}, and the erage day volume of 20 cc./1,000 m.^{3} was the me as the nine-period day average. Siphonohora, Annelida, Amphipoda, Thaliacea, and fish rvae were relatively abundant in this period.

AUGUST TO NOVEMBER 1958

Changes in temperature, salinity, and depth of othermal layer continued. The 0 to 60 m. temerature reached its 1958 peak in this period with n average of 26.3° C. The average 0 to 60 m. linity (34.92‰) increased over the preceding eriod (34.86‰). The average 200 to 300 m. linity continued to decline to 35.00‰. This eriod and June to July 1957 had the lowest 200 300 m. salinities for the nine periods. The depth the top of the thermocline deepened to an erage of 74.0 m.

The low abundance of zooplankton was similar the lows of June to July 1957, December 1957 to arch 1958, and December 1958. Only the averages r Pteropoda and Pelecypoda were above the ght-period average.

DECEMBER 1958

This period was characterized by a marked dease in temperature, rising salinities, and a proessively deepening isothermal layer. As in 1957, e 0 to 60 m. temperature underwent a large drop etween November and December. For 1958 the ecline was from 25.9° C. in November to 24.1° C. December (fig. 6A). The 0 to 60 m. salinity of .07‰ continued to increase from 34.82‰ in July ig. 6B). The 200 to 300 m. salinity (35.06‰) inreased from the previous period. The depth to e top of the thermocline was 93.3 m.

The volume of zooplankton for December 1958 was again lower than the nine-period average. Except for seven groups (*Halosphaera*, Foraminifera, Ostracoda, Amphipoda, Heteropoda, Thaliacea, and fish larvae), however, the plankton during December 1958 was more abundant than in June to July 1957, December 1957 to March 1958, and August to November 1958.

COMPARISON BETWEEN PERIODS

A noticeable feature in the 19 months' observations was the dissimilarity of the hydrographic features for the same months of the 2 years. The 200 to 300 m. salinities for June to July were substantially lower in 1957 than in 1958, whereas the 0 to 60 m. and 200 to 300 m. salinities for August to November were higher in 1957 than in 1958. The depth to the top of the thermocline was shallower in the fall of 1957 than in the fall of 1958. The 0 to 60 m. temperatures reflected the seasonal fluctuations of high temperatures in summer and fall and low temperatures in winter and spring and so did not vary greatly between years for the same months.

Zooplankton was more abundant during the fall of 1957 than in the fall of 1958 (figs. 4 and 9). Previous studies of the distribution of zooplankton in Hawaii have indicated a lack of consistent seasonal change. In 1950 and 1951, volumes were significantly higher during early summer and midsummer than in late summer and fall (King and Hida, 1954). But in 1956, the standing crop of zooplankton was greatest in January, April, and September (Nakamura, 1967).

June to July 1957 and August to November 1958 were alike. Both had similar T-S curves (fig. 7), hence their temperature and salinity characteristics were similar (fig. 8). Both of these periods had low volumes of zooplankton (fig. 9). The day volume of zooplankton for June to July 1957 was equal to the nine-period mean while that for August to November 1958 was low.

December 1957 to March 1958 and May 1958 were also alike. Both had similar T-S curves (fig. 7). Both had low day volumes of zooplankton. A night volume was not available for May 1958.

The two periods (September to November 1957 and April 1958) that had high night and day volumes of zooplankton (fig. 9) also had high 0

to 60 m. and 200 to 300 m. salinities (fig. 8), but their temperatures were quite dissimilar (fig 8).

VARIATIONS OF ZOOPLANKTON AND SALINITY

Of great interest were the coincident variations in the night volumes of zooplankton with variations in the portions of the T-S curves with salinities >35.0‰. As shown in figures 7 and 9, increases or decreases in night volumes of zooplankton appeared with corresponding changes in the salinity. The T-S curves indicated a progressive invasion of high-salinity water in the upper surface layers from June to July 1957 to September to November 1957. The night volumes of zooplankton increased correspondingly during these same periods. In December 1957 to March 1958, less saline waters returned to the uppermost layer of the ocean and the volume of zooplankton dropped below that of the preceding period. Then in April 1958 high-salinity water again invaded the area, and the volume of zooplankton increased. During May 1958 the salinity maximum was about the same as in the previous period, but the surface water was less saline. A night volume of zooplankton was not available for this period. During the next two periods, June to July 1958 and August to November 1958, the occurrence of high-salinity waters decreased progressively. Corresponding decreases also were evident in the night volumes of zooplankton. Water of higher salinity returned again in the uppermost layer during December 1958 coincident with an increase in the night volume of zooplankton.

Thus, waters of high salinity appeared to sustain a greater biomass of zooplankton. The abundance of several groups of zooplankton fluctuated coincidentally with the night volumes and with salinity. These groups were Siphonophora, Chaetognatha, Euphausiacea, decapod Crustacea, and Pteropoda (fig. 10). Because of the correlation of the abundance of these zooplankters with water type, the possibility of finding endemic species appeared favorable. Sherman (1963) found certain species of calanoid Copepoda (Pontellidae) associated with, and thus useful as indicators of, waters of high salinity (North Pacific Central Water) in the Hawaiian area. These groups of zooplankton

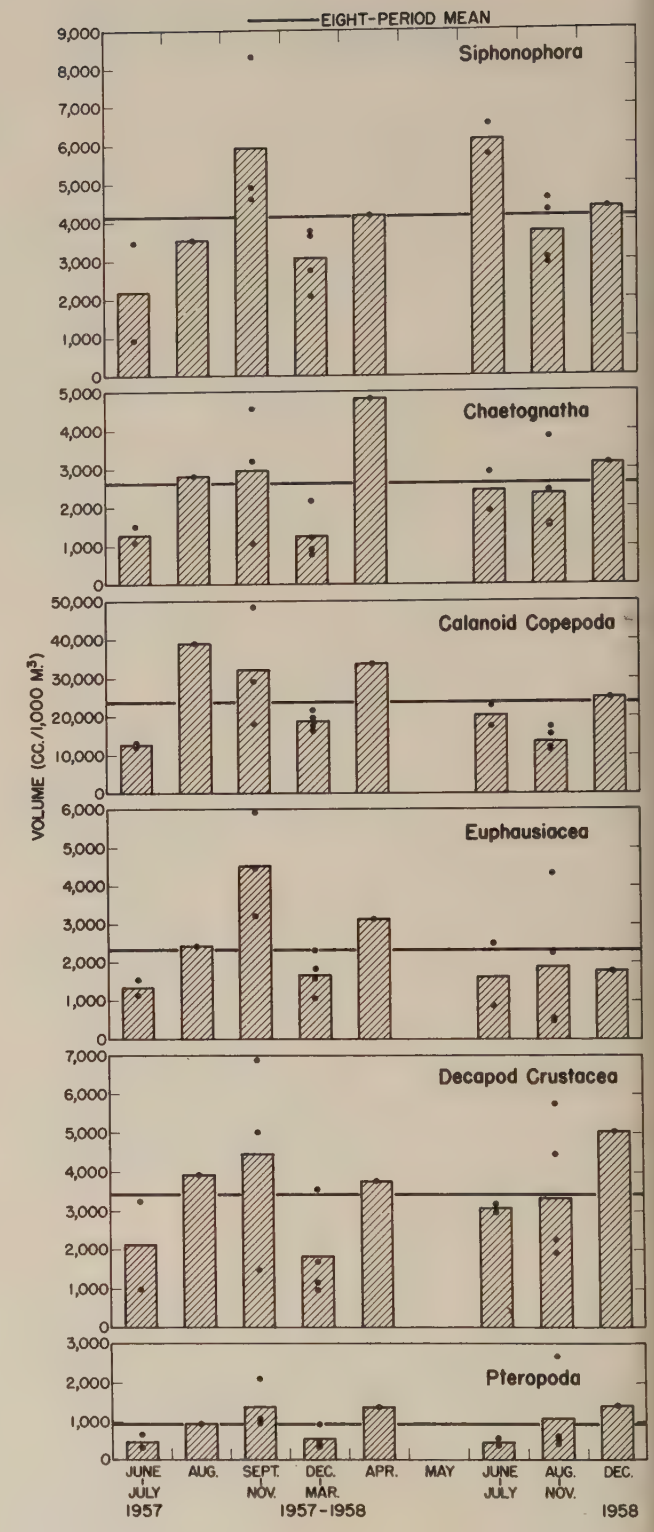

FIGURE 10.—Average abundance of six groups of zooplankton at night during eight periods at the IGY station.

nay include other species possibly useful as ndicators.

SUMMARY

1. Data on zooplankton and hydrography were btained at lat. 21°10.3′ N., long. 158°19.0′ W. rom June 1957 to December 1958. The station was isited once a month, and samples were taken once t highest tide and once at lowest tide. In June 957, the station was occupied for 48 hours to btain samples for studies of diel variation.

2. Volume of zooplankton from the 48-hour eries conformed to the characteristic sinusoidal ariation for the first day, but not for the second. A diatom that prevented drainage of moisture dur- ng determination of the volumes probably caused he high volumes during the morning of the second ay. Variations in abundance were distinctly sinu- oidal for Ostracoda, Euphausiacea, Pteropoda, nd fish larvae. Variations in surface temperature were attributed to heating during the day and cool- ng during the night. Variations in the depth to he top of the thermocline were attributed to inter- al waves.

3. Correlations were significant and positive be- ween day volumes of zooplankton and salinities t the surface and at 0 to 60 m., and for night vol- mes of zooplankton and salinities at 200 to 300 n. Positive correlations for night volumes of zoo- lankton and salinities at 0 to 60 m. and for day olumes and salinities at 200 to 300 m. were very lose to the 5-percent probability. Correlations were significant and negative between both day nd night volumes of zooplankton and depths to he top of the thermocline.

4. The 19 months were divided into nine periods, ach period having a temperature-salinity curve lifferent from the preceding and the following eriods.

5. Salinities and depths to the top of the thermo- line were dissimilar for the same months in 1957 nd 1958. Night volumes of zooplankton were high- st in the fall of 1957.

6. Variations in the night volumes of zooplank- on coincided with variations in salinities > 35.0‰. As the salinity increased, zooplankton increased; s salinity decreased, zooplankton decreased. The bundance of Siphonophora, Chaetognatha, Eu- hausiacea, decapod Crustacea, and Pteropoda fluctuated coincidentally with the night volumes of zooplankton and with salinity.

ACKNOWLEDGMENT

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DDITIONAL REFERENCES ON THE BIOLOGY OF SHRIMP, FAMILY PENAEIDAE [1]

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ABSTRACT

About one thousand references to shrimp are given. Citations are listed alphabetically by author. eferences include those on biology and fishing gear.

The Bureau of Commercial Fisheries Biologi-l Laboratory, Galveston, Tex., is studying the mmercial shrimp of the family Penaeidae that habit the Gulf of Mexico. As background for his research, Chin and Allen (1959) published terature references on shrimp biology. We now resent about one thousand additional references supplement that list. Most references contained our report were published from 1958 through 966, although we have included a few that were reviously overlooked.

Many unpublished reports and theses concern-g Penaeidae came to our attention while we ere compiling the published citations. These un-ublished reports are presented to indicate addi-onal sources of pertinent information. Published nd unpublished references are listed separately.

We have followed generally the procedure used y Chin and Allen (1959). References are listed phabetically by the author's surname. Only ferences concerning shrimp of the family enaeidae are listed, and the subject is limited rimarily to shrimp biology. References concern-g fishing methods and gear, however, are ncluded because they are useful to fishery biolo-sts. We made no special effort to obtain ref-rences to paleontological studies, the shrimp rocessing industry, or shrimp statistics, although e list contains some citations in those fields.

Additional exclusions from the lists of citations hould be noted. We have not included literature published after 1966. Some articles that concern Penaeidae were not available to us for checking the accuracy of citation and have not been included. No attempt was made to include all brief notes on shrimp research and shrimp fisheries that appeared in CFR (Commercial Fisheries Review). These notes are cited in the CFR yearly index. Pertinent lead articles appearing in CFR, however, are included. Many Florida State Board of Conservation Special Mimeographed Reports contained pertinent but limited information on shrimp and were excluded. We often excluded popularized articles derived from more basic reports already cited in our list, abstracts that were followed by complete reports, and unpublished papers that were superseded by published versions. Some duplication of information, however, was unavoidable.

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FOOD, GROWTH, MIGRATION, REPRODUCTION, AND ABUNDANCE OF PINFISH, *LAGODON RHOMBOIDES*, AND ATLANTIC CROAKER, *MICROPOGON UNDULATUS*, NEAR PENSACOLA, FLORIDA, 1963–65

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ABSTRACT

The abundance, growth, age composition, food, migration, and reproduction of the two species were studied at two locations for each species from August 1963 to December 1965. The materials comprised 22 fish collections at each station, taken in about 500 hours of trawling.

The stomach contents of 3,577 pinfish and 2,520 Atlantic croakers indicated that pinfish are omnivorous and croakers carnivorous. Principal foods were vegetation, crustaceans, and polychaetes for pinfish and annelids, fish, and arthropods for croakers. Types of food in pinfish stomachs were similar at all sizes and seasons, but the relative amount of each type differed by season and size of fish. Foods in croaker stomachs differed at the two stations but were similar from year to year. The average food volume in the stomachs varied with time of year, location, and fish size. Volumes of food in stomachs of both species decreased when the fish moved from the estuary.

Length-frequency distributions can be used to estimate age in both species. Pinfish, and possibly croakers, form annuli on their scales. Growth of pinfish and Atlantic croaker varied from year to year.

Some fish of both species had developing gonads in the fall of their first year of life and may spawn. Both species migrate offshore in the fall to spawn. The fry and some adults return to the estuary in the winter and spring.

Abundance of pinfish and Atlantic croakers was highest in late spring and early summer. Pinfish at both stations and croakers at one station were less abundant in 1964 than in 1963 or 1965. Yearly differences in abundance of croakers were not large at the other location.

Pinfish, *Lagodon rhomboides*, and Atlantic croaker, *Micropogon undulatus*, are two of the most abundant species of fish in the Pensacola area and other estuaries in the Southeastern States. The life history of pinfish from areas other than Pensacola has been investigated by Reid (1954), Kilby (1955), Caldwell (1957), and others; and that for Atlantic croaker has been studied by Pearson (1928), Hildebrand and Cable (1930), Wallace (1940), Gunter (1945), Haven (1957 and 1959), and others. The purposes of the present study were to investigate the life histories of these species in the Pensacola Estuary and to contribute to the general knowledge of the biology of these fishes.

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DESCRIPTION OF THE STUDY AREA

The "Pensacola Estuary" (so termed for convenience) has an area of about 370 km.^{2}; it encompasses three bays (two of which are shown in fig. 1) and a sound. The estuary supports commercially harvested stocks of fish and shellfish.

Two stations in the lower estuary were selected for study of pinfish. The sandy bottom at both supports a dense growth of grasses—predominantly turtle-grass, *Thalassia testudinum*, and seagrass, *Ruppia maritima*. Station I is on the north side of Santa Rosa Sound across from Sabine Island, site of the Bureau of Commercial Fisheries Biological Field Station, Gulf Breeze, Fla.; station II is on the south side of Pensacola Bay. Average depth at mean low water is 3.0 m. at station I and

FIGURE 1.—Location of sampling stations in the Pensacola Estuary for pinfish (I and II) and Atlantic croaker (III and IV).

2.5 m. at station II. Salinities at both stations ranged from 4 to 31 p.p.t. and averaged 23 p.p.t. at station I and 24 p.p.t. at station II. Water temperatures were similar at both stations, ranging from 9° to 30° C. and averaging 23° C.

Two locations in the upper estuary were selected for study of Atlantic croakers—station III, off the eastern shore of Escambia Bay, near Trout Bayou, and station IV, off the western shore of the bay. The bottom at both is predominantly mud; attached vegetation is lacking, but station III has isolated oyster reefs. Average depth at mean low water is 2.5 m. at station III and 2.0 m. at station IV. Salinities ranged from 0 to 29 p.p.t., average 15 p.p.t., at station III and from 0 to 27 p.p.t., average 12 p.p.t., at station IV.

MATERIALS AND METHODS

Collections were made with a 5-m. otter trawl of 12-mm. bar mesh. This trawl is the standard "try net" used by commercial shrimpers in Pensacola Bay to find commercial quantities of shrimp. The trawl was pulled behind the 11-m. research vessel *Dolphin* at about 2.5 knots.

All stations were visited 22 times from August 1963 to December 1965; usually 10 trawl hauls (30 minutes) were made at each Atlantic croaker station and 30 hauls (15 minutes) at each pinfish station. Trawling usually began in the middle of the month and lasted 7 days (not necessarily consecutive). The number and duration of hauls were selected to give a reliable estimate of fish abundance. In periods when fish were not abundant the number of trawl samples was reduced to less than half that during periods of abundance.

Treatment of both species after capture was similar. On the boat they were counted, measured to the nearest millimeter of standard length, and whenever possible 50 fish from each 25-mm. size group were preserved in a mixture of 4 percent formaldehyde and sea water of 16 p.p.t. salinity. Fish were slit open to preserve innards (including stomach and gonads). At the laboratory, preserved fish were measured for length and weight (to the nearest millimeter and 0.01 gram) and stomachs and scale samples were removed.

Confidence intervals were computed for the number of fish caught per trawl-haul and on the average length of the fish. Mention of significant differences indicates that confidence intervals, 95 percent confidence coefficient, do not overlap.

Stomach contents of fish captured at the same time were combined by length of the fish—14 to 75 mm. or >75 mm.—and stored in 70 percent ethanol. After identifying and sorting the contents, I blotted them dry and determined their liquid displacement.

Discussion of the volume of stomach contents includes all of the contents but discussion of the composition excludes unidentifiable material; which represented 8.8 percent of the 205.8 ml. of food from 3,577 pinfish stomachs and 25.2 percent of the 58.4 ml. of food from 2,520 Atlantic croaker stomachs. The unidentifiable component of the stomach contents included small particles of inorganic and organic detritus and food digested beyond recognition. Reid (1954) also found large amounts of unidentifiable material in croaker stomachs.

Ages were determined from length-frequency distributions and by examination of scales. The scales were predominantly from fish at the size range where length-frequency distributions indicated a change in age. The scales were taken from the area above the lateral line behind the operculum, stored between sheets of paper, and examined under a monocular microscope. The distances from focus of the scale to the annulus and to the margin of the scale were measured to the nearest 0.1 mm. with an ocular micrometer.

The spawning season extends throughout the winter (about November to March for pinfish and November to February for croakers). In assigning ages to these fish, I used January 1 of the year following the winter of hatching as the first birthday.

I used two methods to study the growth. First, I used the differences in average lengths between consecutive trawling periods to compute the average daily increases in length. Second, I used measurements of scales from yearling pinfish to compute growth increments; increases in length after annulus formation were determined for each sampling date and used to derive daily growth for each season.

To discover movements before spawning, I clipped fins of 26,980 pinfish and 5,269 Atlantic croakers. Fish from different localities were marked differently by removal of either one or both pelvic fins. After the marking, the fish were kept in a tank of circulating water on the boat

until the next trawl-haul was completed, and only fish that seemed healthy were released. The area of release was not fished again for at least 15 minutes. Fish movement could be noted if fish fin-clipped at one station were recaptured at any of the other three stations or at other locations sampled sporadically. I also marked 284 pinfish by attaching an Atkins tag in front of the dorsal fin with nickel wire.

I estimated numbers of eggs in ovaries by measuring the volume of eggs in both ovaries (after most ovarian tissue had been removed) and dividing that value by the average volume of an egg as estimated from measurement of 25 eggs.

PINFISH

Pinfish are one of the dominant animals in the fauna of vegetated areas in the lower Pensacola Estuary. Therefore, I investigated the seasonal and annual change in the food, growth, migration, reproduction, and abundance at two locations from August 1963 to December 1965.

FOOD

Pinfish were omnivorous feeders on the grass flats where stations I and II were located. Gunter (1945) and Reid (1954) on the Gulf of Mexico Coast and Linton (1904) on the east coast of the United States found a large variety of food organisms in pinfish stomachs. I identified 10 phyla of animals and a wide variety of vegetation (including diatoms, filamentous algae, and vascular plants). The type of food varied with season and fish size (table 1), but not by station.

Vegetation contributed 40.6 percent of the total volume of identifiable items (including sand) in the stomachs. It was the dominant food in the summer and fall; the amount usually increased in late spring or early summer and decreased in the late fall. Diatoms were most important in fish less than 76 mm. long, and filamentous algae and vascular plants in larger fish.

Crustaceans, polychaetes, and chordates were dominant in pinfish stomachs in the winter and spring. Small pinfish usually contained a higher total number and volume of small crustaceans than large pinfish. The crustaceans were mainly amphipods, copepods, crabs, cyprids, isopods, mysids, and shrimp. Chordates—amphioxus and (secondarily) fish—were most abundant in large fish. Other animals eaten in smaller amounts were brachiopods, bryozoans, chaetognaths, echinoderms, mollusks, and nemerteans.

The mean volume of food in pinfish stomachs was highest during the summer and early fall (table 2). The increase in the volume usually began in May or June for both size groups of fish and came with increase in ingestion of vegetation. The volume decreased in the fall as fish became more carnivorous. In the fall most fish over 90 mm. long leave the estuary. Amounts of food in the stomachs decrease during the spawning season, as is common in many species of fish.

The mean volume of food in pinfish stomachs was generally low and nearly constant from late fall until late spring, except for a short-term increase in February, when large numbers of caprellid amphipods and polychaetes were found in stomachs of small fish.

TABLE 1.—*Percentage of total volume contributed by differen items in pinfish stomachs collected in the lower Pensacola Estuary at stations I and II in different seasons, 1963–65*

Items in stomachs	Fish length class, season, and number of stomachs [1]								
	< 76 mm.				76–173 mm.				All (3577)
	Spring (537)	Summer (887)	Fall (570)	Winter (122)	Spring (184)	Summer (683)	Fall (575)	Winter (19)	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Crustaceans	58.3	2.8	21.7	44.8	8.7	4.6	5.6	24.9	26.9
Polychaetes	17.3	1.0	2.9	43.4	8.0	4.0	4.0	19.4	9.9
Chordates	3.1	1.5	1.1	10.8	12.5	2.0	2.9	31.3	6.6
Vegetation	4.6	87.2	66.5	.9	21.9	66.4	56.6	23.1	40.6
Sand	12.9	6.7	6.6	.0	44.4	18.9	29.5	.2	13.8
Other [2]	3.8	.8	1.2	.1	4.5	4.1	1.4	1.1	2.2

[1] Numbers of stomachs from both stations are shown in parentheses.

[2] Other items include brachiopods, bryozoans, chaetognaths, echinoderms, mollusks, and nemerteans.

TABLE 2.—*Average volume of stomach contents of small and large pinfish collected in the lower Pensacola Estuary at stations I and II in the months of sampling, 1963–65*

Month	Fish length class			
	<76 mm.		76–173 mm.	
	Stomachs Examined	Average contents	Stomachs Examined	Average contents
	No.	*Ml.*	*No.*	*Ml.*
January	32	0.01	1	0.07
February	90	.05	18	.08
March	6	.01	2	.08
April	341	.01	111	.07
May	190	.01	71	.11
June	326	.02	174	.11
July	296	.03	214	.12
August	265	.06	295	.14
September	183	.03	239	.07
October	228	.04	289	.08
November	159	.01	47	.03

AGE AND GROWTH

Pinfish were aged by using length-frequency data and by examination of scales. Length frequencies have been used to age pinfish (Caldwell, 1957) but scales have not. Pinfish from the two stations were of similar lengths; therefore, length-frequency data for the stations were pooled (fig. 2). The bimodal length-frequency distribution indicates at least 2 year-classes of pinfish.

Average length of pinfish at annulus formation, as determined by scale measurements, was similar to the average length of fish measured in early spring. Most of the annuli formed in April of both 1964 and 1965. The percentage of yearling fish that showed an annulus in different months in 1964 and 1965 (data combined) were as follows (number of fish in parentheses): January—12 percent (57); February—13 percent (85); March—0 percent (2); and early May—100 percent (42). Back-calculation of fish lengths showed that the 1963 and 1964 year classes formed a year-mark at average lengths of 61 and 78 mm., respectively. Fish from these year classes were at this size as yearlings in March or April. The average length of fish entering their third year of life was 127 mm. (15 fish) at the time of annulus formation.

The average size of pinfish varied during the different years (table 3). Yearly differences in average size result from a number of factors such as differences in hatching time and growth rate. Standard lengths of fish caught by trawling and seining during the study were 13 to 152 mm.; fish

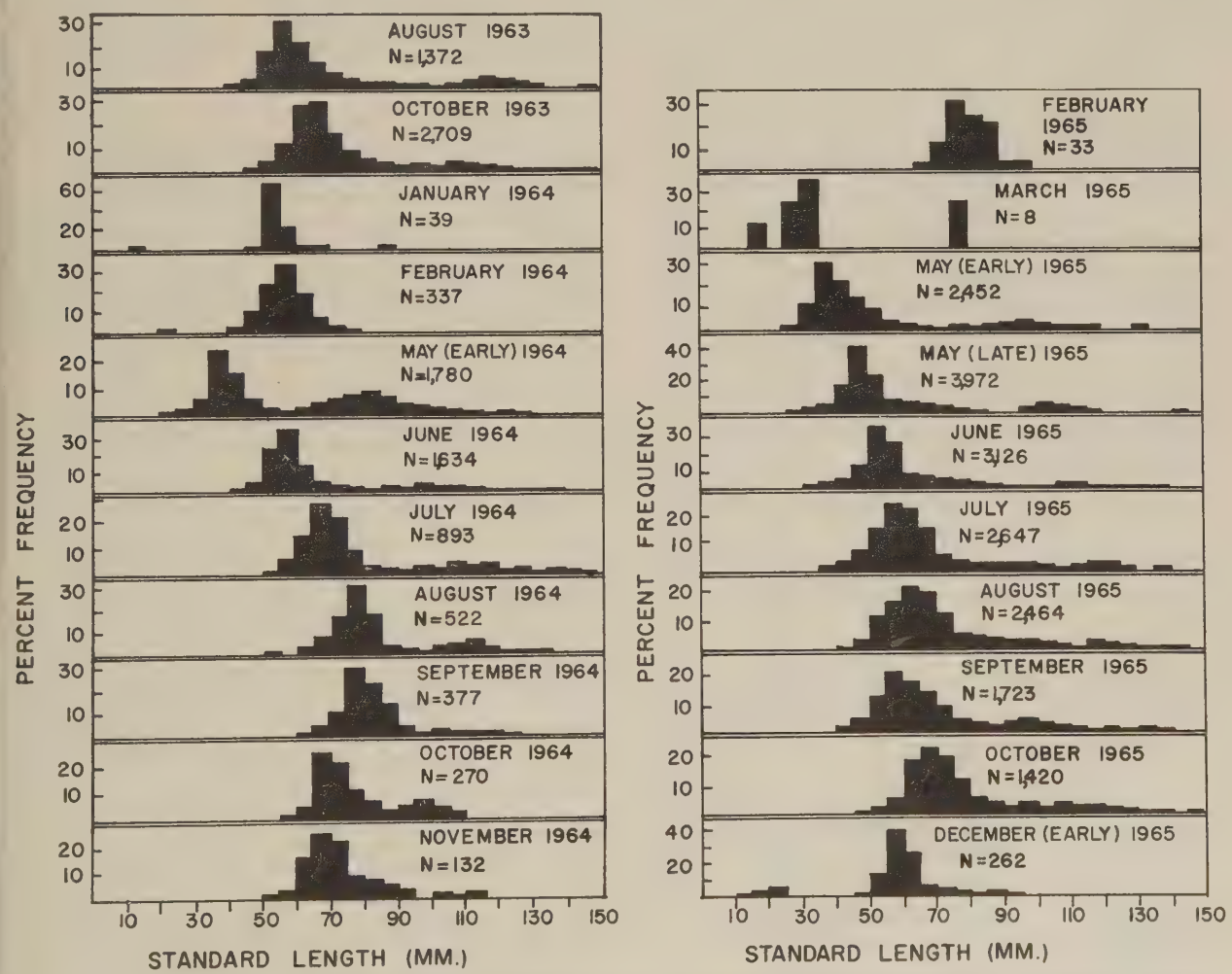

FIGURE 2.—Length-frequency distribution of pinfish caught in the lower Pensacola Estuary at stations I and II, 1963–65.

TABLE 3.—*Standard lengths of pinfish of age-groups 0, I, and II in the lower Pensacola Estuary at stations I and II, 1963–65*

Date	Age-group 0			Age-group I			Age-group II		
	Fish	Length		Fish	Length		Fish	Length	
		Average	Range		Average	Range		Average	Range
1963	*Number*	*Mm.*	*Mm.*	*Number*	*Mm.*	*Mm.*	*Number*	*Mm.*	*Mm.*
August 30–September 6	1,316	60	44–102	56	118	105–145	0		
October 29–November 1	2,642	67	47–107	67	117	107–145	0		
1964									
January 10–15	1	14		38	47	43–83	0		
February 28–March 3	1	22		336	56	43–79	0		
May 12–14	1,008	39	21–60	771	82	61–123	1	128	
June 29–July 1	1,567	57	42–79	65	100	81–130	2	132	129–136
August 3–5	829	68	52–93	62	109	91–140	2	136	136–137
August 31–September 2	438	76	50–94	84	115	96–133	0		
September 28–30	352	80	60–101	25	112	102–128	0		
October 30–November 3	270	77	59–109	0			0		
November 23–25	132	72	53–110	0			0		
1965									
January 12	1	30		0			0		
March 3	0			33	81	69–97	0		
March 29	6	28	19–32	2	78	77–79	0		
May 6–12	2,369	42	25–69	82	96	76–116	1	134	
June 1–3	3,917	48	28–78	53	102	77–111	2	137	136–138
June 25–29	3,098	54	33–94	21	112	97–130	7	136	131–143
August 2–4	2,623	59	35–105	22	118	113–125	2	136	135–136
August 30–September 1	2,414	64	42–109	49	120	110–137	1	141	
September 22–24	1,706	68	45–110	17	123	113–139	0		
October 25–27	1,383	71	49–116	37	121	112–146	0		
December 6–8	8	20	14–22	254	60	47–92	0		

caught at the sampling stations were 14 to 146 mm. long.[1]

Pinfish growth rates computed from changes in lengths between consecutive trawling periods varied with age group and season. Daily increase in length averaged 0.19 mm. for 0-group pinfish and 0.12 mm. for yearlings. Growth of both age groups slowed as the seasons progressed from spring to winter. Daily increase in length of 0-group pinfish averaged 0.32 mm. in the spring, 0.23 mm. in summer, and 0.01 mm. in fall; yearling pinfish averaged 0.32 mm. in the spring, 0.21 mm. in summer, −0.04 mm. in fall, and −0.02 mm. in winter. Caldwell (1957) also observed maximum growth in the spring and negligible growth in the fall and winter.

Annual growth rate of yearling pinfish, estimated from increase in length after annulus formation, was closely similar to that based on increase in measured lengths, but seasonal growth rates determined by the two methods differed. Annual increase in length computed from scale measurements averaged 0.14 mm. per day, and seasonal increases averaged 0.12 mm. per day in the spring, 0.14 mm. in the summer, 0.20 mm. in the fall, and 0.09 mm. in the winter.

[1] Standard length = 0.85 fork length or 0.78 total length on the basis of measurements of 100 fish, 44 to 101 mm. long.

MIGRATION AND REPRODUCTION

Limited data on estuarine movements of pinfish were obtained from recaptures of fin-clipped or tagged fish. Of 26,980 pinfish fin-clipped, 234 (0.87 percent) were recaptured at the area of original capture during the trawling period in which they were released and only 47 (0.17 percent) were recovered 1 month or more after marking. There could be several reasons for the low recapture rates. The proportion of the population marked was small, the marking mortality was high, or unmarked fish from other areas were moving in. Of the 47 fish recovered 1 month or more after marking, 39 were caught at the station of release, and eight had moved either from station I to station II or from station II to station I (five did so in the 3 principal months of the spawning migration—August, September, and October). Of 284 pinfish tagged in April 1964, two were recaptured—one in July about 125 m. from where it was tagged and the other in October about 3 km. closer to the mouth of the bay.

On the basis of results of trawling and seining, I believe that most pinfish remain over the grass flats where they live in the spring until they migrate out of the estuary in late summer and fall. Most appear to move very little in the summer, but a few may wander over the grass flats. Fish

may congregate in response to abundance or scarcity of food during this time but schools are not formed.

At the start of the spawning migration into the Gulf of Mexico, however, the pinfish school in large numbers. These schools seem to consist of fish of the same age. Large numbers of pinfish captured in Chesapeake Bay in October, as noted by Hildebrand and Schroeder (1927), probably were schools of seaward migrants. Aggregations of pinfish have also been seen in the Gulf of Mexico (Springer, 1957). In the late winter and spring, I have observed schools of pinfish in Santa Rosa Sound, Fla., that were probably returning from the Gulf of Mexico. Most of these fish were in their second year of life. Few fish live to reenter the estuary in their third year.

The stage of gonad development before migration varied. In most years, maturation of gonads probably takes place during the migration or while the fish are at or near the offshore spawning site. In October 1965, when most fish over 80 mm. were mature enough to permit determination of sex, the gonads ranged from the late stage 1 to the late stage 3 of Homans and Vladykov (1954)—gonads growing in size; yellow, opaque eggs microscopic to visible, and testes pinkish to flesh-colored or white and slightly distended. None had gonads that would produce milt or eggs when pressed (stage 4 or 5). Because the examination of scales showed that most fish under about 110 mm. were in their first year of life, it is likely that some 0-group fish and all yearling pinfish spawn.

Eight pinfish 111 to 152 mm. long had ovaries with eggs that were mature enough for counting; eggs in smaller fish were too small to count accurately. The diameters of eggs were 0.09 to 0.66 mm. (average 0.38) and the estimated numbers of eggs were 7,700 to 39,200 (average 21,600). Caldwell (1957) examined a pinfish 157 mm. long which had an estimated 90,000 eggs that averaged about 0.5 mm. in diameter.

ABUNDANCE AT THE SAMPLING STATIONS

Pinfish are present in moderate numbers in the deeper parts of Pensacola Bay in the summer; they are most abundant in the southern part of the estuary in extensive flats covered with turtle grass. Reid (1954) and Kilby (1955) also observed that pinfish were most numerous in vegetation along the Gulf Coast of Florida. Pinfish are distributed unevenly on the flats, as they tend to aggregate in response to the environment—concentrations of food especially attract them.

Despite the wide confidence limits on the average number of fish caught, seasonal trends are clearly evident (table 4). Because the periods of maximum and minimum abundance, and monthly changes in

TABLE 4.—*Pinfish caught per 15-minute trawl-haul in the lower Pensacola Estuary, 1963–65* [1]

Date	Station I			Station II			Averages both stations
	Average	Confidence interval 95 percent	Range	Average	Confidence interval 95 percent	Range	
	Number	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
1963							
August 30–September 6	312	183–441	5–791	66	21–112	6–219	214
October 29–November 1	66	35– 96	0–253	59	48– 70	9–145	62
1964							
January 10–15	1	0– 3	0– 23	[2] 0	[2] 0– 0	0– 1	1
February 28–March 3	4	1– 7	0– 40	8	0– 16	0–111	6
May 12–14	19	11– 28	0– 97	40	26– 54	2–136	30
June 29–July 1	63	11–114	1–521	110	65–155	1–412	86
August 3–5	11	4– 18	0– 77	19	10– 28	0– 95	15
August 31–September 2	14	9– 19	0– 45	4	3– 5	0– 10	9
September 28–30	10	6– 14	0– 40	3	1– 4	0– 20	6
October 30–November 3	6	3– 10	0– 33	3	1– 4	0– 9	4
November 23–25	4	1– 7	0– 43	1	0– 1	0– 4	2
1965							
January 12	0			[2] 0	0– 1	0– 1	[2] 0
March 3	1	0– 2	0– 2	6	0– 18	1– 23	3
March 29	1	0– 4	0– 5	[2] 0	0– 1	0– 1	1
May 6–12	58	32– 84	0–208	29	12– 47	0–214	44
June 1–3	120	82–157	0–299	80	49–112	0–326	100
June 25–29	142	98–186	4–409	231	177–286	3–541	186
August 2–4	99	61–138	3–325	144	75–212	0–776	122
August 30–September 1	40	26– 52	1–123	92	52–132	0–469	66
September 22–24	22	15– 29	1– 83	68	45– 92	0–218	45
October 25–27	19	13– 26	0– 71	30	18– 41	0–137	25
December 6–8	8	3– 12	0– 51	2	1– 2	0– 6	5

[1] 30 trawl-hauls were made at each station on each visit, with the following exceptions (number of hauls in parentheses): Aug. 30–Sept. 6, 1963—station I (15), station II (10); Jan. 12, Mar. 3, and Mar. 29, 1965—each station (5).

[2] Less than 0.5.

abundance, were similar from year to year, I assume that average catch gives a reasonably good estimate of general abundance.

Pinfish young (O-group) and older migrants returning to the estuary began to arrive on the grass flats at both stations in late November and early December. Trawling did not capture young fish in numbers indicative of their actual abundance but seining caught large numbers of them near both stations. The migration continued until the population had reached a maximum by late June. The month that young first appear seems to depend on conditions offshore, because salinity and temperature changes in the estuary show no relation to the time of migration. Progressively fewer fish were captured after June because of natural mortality and emigration.

Pinfish abundance changed from year to year. If catch in August (a month fished in each of 3 years) is used as an indicator of yearly changes in abundance, pinfish were significantly less plentiful in 1964 than in 1963 or 1965. Pinfish were most numerous at station I in 1963 and at station II in 1965. The number of fish caught in the winters of 1963–64 and 1964–65 did not differ from November to February at station I and November through April at station II.

The numbers of fish caught at the two stations at each sampling time were similar, differing significantly only in August and September of each of the 3 years. This period marks the start of migration out of the estuary; significant changes in abundance might, therefore, be expected if the fish left one station earlier than the other.

ATLANTIC CROAKER

Atlantic croakers are one of the dominant fish in the upper Pensacola Estuary. Therefore, I investigated seasonal and annual change in the food, growth, migration, reproduction, and abundance at two locations from August 1963 to December 1965.

FOOD

Atlantic croakers are carnivorous (table 5). The animal food in the present collections included five phyla and numerous species. Vegetation and sediments in some stomachs were probably taken incidentally while fish were capturing animal food.

TABLE 5.—*Percentage of total volume contributed by different items in Atlantic croaker stomachs collected in the upper Pensacola Estuary at stations III and IV in different seasons, 1963–65*

Items in stomachs	Fish length class, season, and number of stomachs [1]								
	<76 mm.				76–173 mm.				All lengths (2,520)
	Spring (488)	Summer (222)	Fall (63)	Winter (230)	Spring (317)	Summer (981)	Fall (162)	Winter (7)	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Arthropods	25.8	3.2	4.1	20.6	26.5	28.0	7.0	8.1	14.3
Mollusks	2.3	3.3	.0	.1	8.4	9.2	1.7	.0	3.5
Annelids	43.4	74.2	92.6	51.6	26.4	40.0	66.9	89.5	61.5
Nemerteans	.6	1.4	.0	.0	.1	.2	.3	.0	.3
Fish	19.9	11.9	.9	27.1	35.1	17.0	17.3	.0	15.9
Vegetation	1.5	1.5	.0	.2	1.8	4.3	4.2	1.3	2.0
Sediments	6.5	4.5	2.4	.4	1.7	1.3	2.6	1.1	2.5

[1] Numbers of stomachs from both stations are shown in parentheses.

Annelids were the major food except in large fish in the spring, when fish were dominant. Pearson (1928), who collected along the Gulf Coast, and Roelofs (1954), on the Atlantic Coast, found that annelids were dominant and that the other foods listed in table 5 were present in the stomachs of young croakers.

Fish were most common in Atlantic croakers over 75 mm. long. At station III, fish were most plentiful in stomachs in the spring and summer. At station IV, fish were most abundant in the winter in croakers less than 76 mm. long and in the spring in croakers over 75 mm.

Arthropods, chiefly crustaceans, were most plentiful in small fish in the winter and spring and in large fish in the spring and summer. The most important crustaceans were copepods, amphipods, isopods, mysids, shrimp, and crabs; larger forms were most common in stomachs of large fish. Insects—mainly tendipedids, dytiscids, and anisopterans—made up 67 percent of the arthropods in stomachs collected at station IV after heavy runoff in the spring.

Mollusks and nemerteans were minor constituents in the stomachs of Atlantic croakers. Mollusks were most plentiful in stomachs of large fish in the spring and summer.

The volume of food in croaker stomachs was greatest in the winter and spring; average for 768 fish under 76 mm. long was 0.02 ml. and for 324 fish over 75 mm. long, 0.04 ml. Food volumes decreased in the summer and fall; for 285 fish less than 76 mm. long the average volume was 0.01 ml. in both summer and fall, and for fish longer than

5 mm., the average was 0.03 ml. in the summer 981 fish) and 0.01 ml. in the fall (162 fish).

AGE AND GROWTH

I determined the age of Atlantic croakers by using length-frequency data. Fish from the two stations were of similar lengths, except for some segregation by size according to salinity (see next paragraph). Length-frequency data for the stations were, therefore, pooled (fig. 3). The data indicated that only 18 of 19,107 croakers (less than 0.1 percent) were in their second year of life.

Scales may be suitable for age determination of Atlantic croakers from the study area, but this method was unacceptable for Lake Pontchartrain fish (Suttkus, 1955). In the Pensacola Estuary, 3 of 201 Atlantic croakers had what may have been an annulus on their scales. The age of fish as indicated by scales conformed to that indicated by length-frequency data.

Changes in the size distribution of Atlantic croakers within this estuary occur when the larger fish move to areas of higher salinity. A faster growth rate in more saline waters would accentuate this size difference. In June 1964, 620 croakers averaged 70 mm. at station IV, and 1,290 averaged 76 mm. long at station III; in collections 8 and 12 miles below station III, 283 fish averaged about 94 mm. Length differences were still apparent in July. Average lengths were 90 mm. at station IV (149 fish), 91 mm. at station III (742 fish), and 98 mm. 12 miles below station III (155 fish).

The average size of Atlantic croakers varied during the different years (table 6) as a result of differences in hatching time and growth rate. In 1965, fish arrived in the estuary earlier than in 1964;

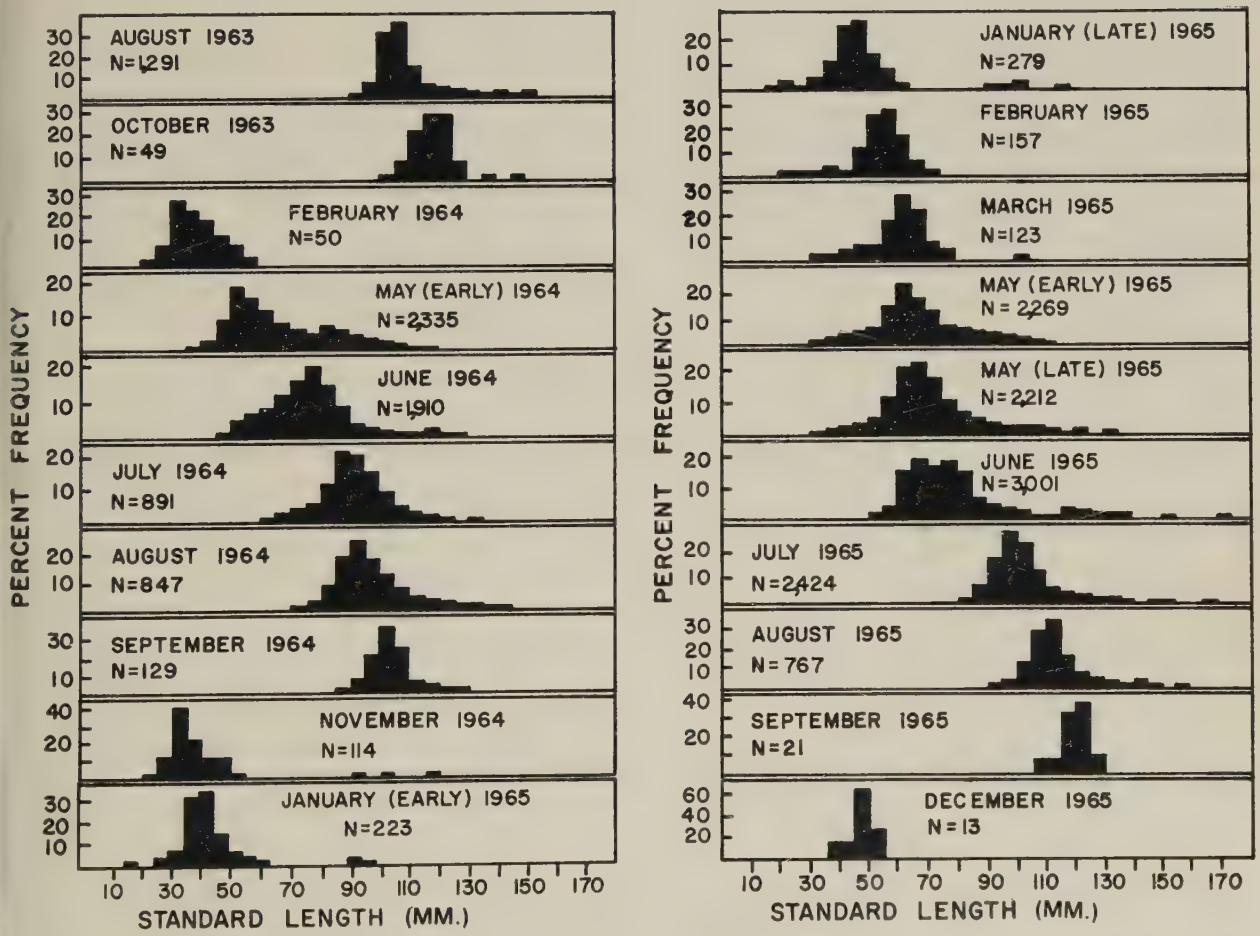

FIGURE 3.—Length-frequency distribution of Atlantic croakers caught in the upper Pensacola Estuary at stations III and IV, 1963–65.

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TABLE 6.—*Standard lengths of Atlantic croakers of age-groups O and I in the upper Pensacola Estuary at stations III and IV, 1963–65*

Date	Age-group O			Age-group I		
		Length			Length	
	Fish	Average	Range	Fish	Average	Range
	Number	*Mm.*	*Mm.*	*Number*	*Mm.*	*Mm.*
1963						
August 22–29	1,291	107	91–152	0		
October 21–24	49	117	103–146	0		
1964						
January 6–14	2	32	24– 40	0		
February 24–27	50	38	20– 55	0		
May 5–11	2,335	65	35–117	0		
June 22–25	1,909	75	45–128	1	166	
July 27–30	891	91	61–131	0		
August 24–27	847	94	70–140	0		
September 21–24	129	102	86–125	0		
October 26–29	0			0		
December 8–10	111	35	24– 50	3	105	94–118
1965						
January 5–7	220	41	17– 60	3	93	91– 96
January 26–28	274	45	15– 64	5	102	94–118
February 23–March 2	157	54	21– 74	0		
March 22–31	122	61	30– 79	1	112	
May 3–7	2,269	67	34–113	0		
May 25–28	2,211	68	34–123	1	132	
June 21–24	2,999	74	51–136	2	163	153–173
July 26–30	2,422	99	68–151	2	164	161–168
August 24–27	767	111	93–155	0		
September 20–21	21	118	106–129	0		
December 1–2	13	47	38– 53	0		

therefore, they were larger in the winter, and from January through August grew at a faster rate (0.30 mm. per day in 1964, 0.36 mm. per day in 1965) so that in August they averaged 17 mm. longer than in 1964. Growth was greatest in the spring in 1964 and in the summer in 1965, and maximum growth was in July in both years (0.60 mm. per day).

MIGRATION AND REPRODUCTION

Migrations of Atlantic croakers are extensive. In December and January the young begin to enter the estuary from spawning grounds in the Gulf of Mexico and move to areas of low salinity. Haven (1957) noted that these fish move up the estuary in the salt-water "wedge" near the bottom. Two days of trawling (February 10–11, 1964) at all depths near the mouth of the Pensacola Estuary, however, caught no young croakers.

Atlantic croakers of age-group O appeared earlier and were more abundant at station IV in the years when estuarine water temperatures were relatively high in November and December. The average temperatures in November–December were: 1963—14.0° C., 1965—16.4° C., and 1964—19.2° C. In the winter of 1963–64 the first young-of-the-year croakers were caught in early January. In the winter of 1964–65 and 1965–66 they appeared in late November and early December (in the greater numbers in the winter of 1964–65). Young fish appeared first and in greatest abundance in areas of low salinity (station IV). They moved to areas of higher salinity as they grew and appeared in the lower estuary (stations I and II) in late spring. Fish caught at stations I and II were never as small as fish captured in the upper estuary near the beginning of the fry migrations.

Of 5,269 fin-clipped Atlantic croakers only 6 (0.1 percent) were recaptured, and only 2 of these had been marked at least 1 month before recapture. None had left the area of marking.

The migration of Atlantic croakers out of the estuary begins in late summer and ends before November. All fish probably leave the estuary; no croakers have been captured after the period of gulfward migration until the newly hatched fish enter the estuary.

Pearson (1928), Suttkus (1955), and Roithmayr (1965) found that, along the Gulf Coast, Atlantic croakers spawn at the end of their second year of life. In the Pensacola Estuary, most croakers had developing gonads in the fall of their first year of life. Most females and males examined had well-developed gonads (stage 2 or 3 of Homans and Vladykov, 1954). Although it is possible that the developing eggs are retained, these croakers may spawn in their first year of life.

Ovaries of 18 croakers, 101 to 145 mm. long,

aught in the fall of 1963, near the end of their irst year of life, had an average of 41,200 eggs. The diameter of eggs was 0.02 to 0.72 mm. and veraged 0.34 mm. Hildebrand and Cable (1930) ndicated that a mature egg probably has a diam- ter less than 1 mm. The eggs in the large yellow varies had fat globules.

ABUNDANCE AT THE SAMPLING STATIONS

Atlantic croakers are most abundant in low-alinity areas in the Pensacola Estuary. Young (O-group) enter the estuary in the winter and pring and move out in the fall. Fish in the estuary re rarely more than 10 months old.

Monthly changes in abundance (table 7) are aused primarily by migrations and, to a lesser xtent, by natural mortality. In the winter young roakers move rapidly from the Gulf to the upper stuary; catches were largest at the station of owest salinity. The number of fish increases to a maximum in May or June. Yearly differences in abundance were small at station III but croakers were most numerous at station IV in 1965.

SUMMARY

Life histories of pinfish and Atlantic croaker in the Pensacola Estuary were studied from August 1963 to December 1965. Their food, growth, age composition, migrations, reproduction, and abundance were studied from fish collected at intervals of about 1 month for 2½ years. Each species was sampled 22 times at each of two stations.

Feeding, migrations, and other aspects of the biology of pinfish from the Pensacola Estuary change seasonally. They spawn in the Gulf of Mexico in winter. Young and adults enter the estuary in the winter and spring where they congregate on grass flats and feed primarily on animals—crustaceans, polychaetes, and chordates—and attain maximum abundance in June. From June until the fall migration pinfish apparently move only short distances over the grass flats and are primarily herbivores. The amount of food in the stomachs is at its highest level at this time. The gonads of all fish except the smaller ones in their first year of life begin to develop in the fall; ovaries contain about 22,000 developing eggs. The maturing pinfish school and leave the estuary in the fall. Food of the remaining fish includes fewer plants, and the amount of food in their stomachs decreases. Usually pinfish form the first annulus on their scales in April of their second year of life.

The life history of Atlantic croakers from this area is similar to that of pinfish. Croakers spawn in the Gulf of Mexico in the late fall and winter,

TABLE 7.—*Atlantic croakers caught per 30-minute trawl-haul in the upper Pensacola Estuary at stations III and IV, 1963–65*[1]

Date	Station III			Station IV			Average both stations
	Average	Confidence interval 95%	Range	Average	Confidence interval 95%	Range	
1963	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
August 22–29	107	63–150	25–229	22	18– 27	11– 34	64
October 21–24	3	2– 5	0– 8	2	1– 2	1– 2	2
1964							
January 6–14	[2] 0	[2] 0– 0	0– 1	[2] 0	[2] 0– 0	0– 1	[2] 0
February 24–27	0			5	0– 10	0– 16	2
May 5–11	280	218–342	202–463	9	7– 12	5– 16	144
June 22–25	228	81–375	11–527	62	37– 87	19–100	145
July 27–30	74	54– 94	27–110	13	9– 21	5– 26	44
August 24–27	48	21– 74	1–134	41	28– 54	13– 74	44
September 21–24	11	3– 18	1– 26	2	1– 4	0– 7	6
October 26–29	0			0			0
December 8–10	0			11	1– 22	0– 38	8
1965							
January 5–7	1	0– 5	0– 3	22	8– 36	3– 66	17
January 26–28	1	0– 1	0– 1	28	6– 50	0– 77	20
February 23–March 2	2	0– 4	1– 3	15	0– 33	0– 83	12
March 22–31	6	3– 8	2– 14	6	1– 12	0– 26	6
May 3–7	85	43–127	3–172	174	128–220	89–320	130
May 25–28	102	80–124	67–172	495	349–642	135–801	298
June 21–24	221	145–297	67–436	332	284–380	239–408	276
July 26–30	93	17–170	1–378	149	87–212	76–353	121
August 24–27	27	18– 36	10– 47	50	35– 65	17– 85	38
September 20–21	4	0– 8	0– 8	0			2
December 1–2	0			3	0– 10	0– 13	2

[1] 10 trawl-hauls were made at each station per month with the following exceptions (number of hauls in parentheses): Station III, 1964—Dec. 8–10 (3); 1965—Jan. 6 (3), Jan. 28 (4), Mar. 2 (3), Sept. 21 (5), and Dec. 2 (2); Station IV, 1965—Sept. 20 (5), and Dec. 1–2 (5).

[2] Less than 0.5.

and the young move rapidly to the upper estuary; adults rarely reenter the estuary. The young arrive earlier and are more abundant in the winter of years of high water temperatures in November and December but maximum abundance, reached in May or June, seems to be unrelated to water temperatures. The volume of food in the stomachs of croakers is greatest during the first few months after their arrival in the upper estuary. While in the estuary they feed primarily on animals; polychaetes are the dominant food of all sizes of fish. Mollusks, large crustaceans, and fish are eaten in greater amounts as croakers become larger. As croakers grow, the larger individuals move down the estuary causing a stratification by size along the salinity gradient. Migration to the Gulf and gonadal development begin in the late summer and fall. Ovaries of fish in their first year of life contain about 40,000 eggs.

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CONDITIONS RELATED TO UPWELLING WHICH DETERMINE DISTRIBUTION OF TROPICAL TUNAS OFF WESTERN BAJA CALIFORNIA[1,2]

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ABSTRACT

Six oceanographic cruises were made off the west coast of southern Baja California in June through November, 1959–66, and some of the results were compared with contemporaneous fishery data on the distribution of yellowfin tuna, *Thunnus albacares*, and skipjack tuna, *Euthynnus pelamis*. The object was to test the hypothesis that the tunas generally do not aggregate in waters cooler than 20° C. even when suitable food is abundant, but do aggregate in warmer waters provided that suitable food is abundant. The measure of abundance of suitable food was the concentration of the pelagic red crab *Pleuroncodes planipes*, a herbivore which is the principal component of the tunas' diet in the Baja California region.

The results supported the hypothesis very well except on the cruise made in June. Then the coastal upwelling was still strong and some tuna entered waters as cold as 17° C., but no colder, where red crabs were abundant. Areas with temperatures 20° C. or over were very limited, and food was generally scarce in them, although it was plentiful in the extensive areas of upwelled water under 17° C. On each of the other five cruises, which covered the period of decay and disappearance of upwelling, extensive areas contained abundant food at temperatures at and over 20° C. Tunas aggregated in or very near those areas, and nowhere else in the cruise region. Red crabs were most abundant in places where their food, phytoplankton (measured as surface chlorophyll *a*), was most plentiful, and in the upwelling season these places were areas of cool upwelled water. The tunas aggregated at first around the edges of the cool areas, which were rich in chlorophyll *a* and red crabs. Later, when surface temperatures in the cores of the cool areas rose past 20° C., the tunas aggregated there as well. Eventually, after all upwelling had ceased, the distribution of surface chlorophyll *a*, red crabs, and tunas became rather uniform off the Baja California coast.

These relations are considered to support the following general statement of tuna ecology, for which there was some prior justification: temperatures set limits of total range, sometimes differently for different species, and food supply determines distribution within the range limits.

Tuna avoid the Cape San Lucas front when it contains water below 20° C., but otherwise the front may have no effect upon them. There is no evidence of aggregation of tuna prey in the front.

As a result of the association of red crabs with phytoplankton (surface chlorophyll *a*) tuna generally occur in the parts of the Baja California region where surface chlorophyll *a* concentrations are relatively high, provided that surface temperatures are not below 20° C. If the region could be thoroughly and frequently monitored for surface temperature and surface chlorophyll *a* during a tuna season, areas of probable tuna aggregation could be specified. It may eventually be practicable to do the monitoring from ships, aircraft, or satellites. It would not suffice to monitor surface temperature only.

Most species of tunas have a wide range in the world's oceans. Their distribution appears to depend mainly upon two oceanic properties: temperature, which sets limits of total range for each species; and standing stock of animals that tuna will eat, which determines distribution within the range limits. This opinion is reasonable, widely held, and supported by a large amount of information (Blackburn, 1965).

Much of the evidence for the hypothesis, however, is indirect. Because tunas are difficult subjects for experiments, tuna ecology depends upon

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comparisons between occurrences of tuna and distributions of properties as observed in the ocean. Many of these comparisons have been based on noncontemporaneous data. Distributions of tuna prey have been inferred from other property distributions more often than they have been observed. Different kinds of data on tuna occurrence, some of better quality than others, have been used. The tendency has existed to compare tuna data with environmental data on broad scales of space and time, a procedure which is more suitable for generating hypotheses than for testing them.

The hypothesis must survive tests of detailed close comparison between tuna and environment on narrow scales of space and time if it is to be accepted, but very few suitable tests have been made. The need for a good test became particularly evident about 5 years ago, when plans were being made for a series of oceanographic surveys of the eastern tropical Pacific Ocean (the EASTROPAC Expedition, 1967–68). One of the purposes of the expedition was to identify areas, outside the limits of existing fisheries, in which skipjack tuna, *Euthynnus pelamis*, might be abundant. It was necessary to know whether that purpose would be served by measuring standing stock of tuna prey routinely on the expedition.

The STOR (Scripps Tuna Oceanography Research) Program made a series of cruises off the west coast of southern Baja California to test the hypothesis. This paper gives the results of the test. The area off southern Baja California was selected for the following reasons:

1. It is the area closest to the Scripps Institution of Oceanography in which both yellowfin tuna, *Thunnus albacares*, and skipjack tuna occur regularly in abundance. These are the principal species taken in American tuna fisheries in the eastern tropical Pacific. The most detailed previous study of tuna ecology in the eastern tropical Pacific dealt particularly with yellowfin tuna (Blackburn, 1962, 1963), but the need is now pressing for work on skipjack tuna as well.

2. Yellowfin and skipjack tuna move seasonally from the tropics into the area west of Baja California and then back to the tropics. This shift has been shown by tagging experiments (Schaefer, Chatwin, and Broadhead, 1961; Fink, unpublished). The northern range limits of both species are generally in the area or south of it (fig. 1). Property distributions in the area should, therefore, show which properties correspond with range limits and which do not.

3. The food chain of yellowfin and skipjack tuna is shorter and simpler in the Baja California area than elsewhere in the eastern Pacific in ways that were expected to facilitate the study. In the other areas both tuna species consume a great variety of fishes, crustaceans, and cephalopods, most of which are presumably carnivores (Alverson, 1963). Off the west coast of Baja California, however, both tuna species feed mainly on the galatheid crab *Pleuroncodes planipes* (Alverson, 1963), which is a facultative herbivore and sometimes the dominant herbivore in the area (Longhurst, Lorenzen, and Thomas, 1967). *P. planipes*, frequently called red crab, is commonly pelagic, easy to collect in nets from a research ship, and conspicuous (easy to sort) in net catches. It is the principal species of the micronekton—about 80 percent of the total, by volume—in the area west of southern Baja California (Blackburn, 1968). Boyd (1967) recently published a good illustration.

CalCOFI (California Cooperative Oceanic Fisheries Investigations) has provided much oceanographic information about waters west of Baja California, through a program of seasonally repetitive cruises that began in 1949. IATTC (Inter-American Tropical Tuna Commission) has been recording commercial catches of yellowfin and skipjack tunas in the same area and elsewhere since the beginning of 1951. The IATTC tuna data were suitable for the proposed study, but the CalCOFI oceanographic data were not very suitable because they had been obtained for other purposes. The CalCOFI cruises generally covered only about half the area that yellowfin and skipjack occupy off Baja California (see example in fig. 7); they frequently missed the period when the tunas were most widespread in the area; and they seldom provided any information on phytoplankton or on animals eaten by tuna. It was necessary, therefore, to make special cruises for tuna ecology studies. Five such cruises, together with one CalCOFI cruise that was equipped to serve the same purpose, were made. They covered most of the period of the year (in different years) when tropical tunas occur off Baja California.

The hypothesis to be tested was that yellowfin and skipjack tunas generally do not occur in waters of surface temperature below 20° C., even

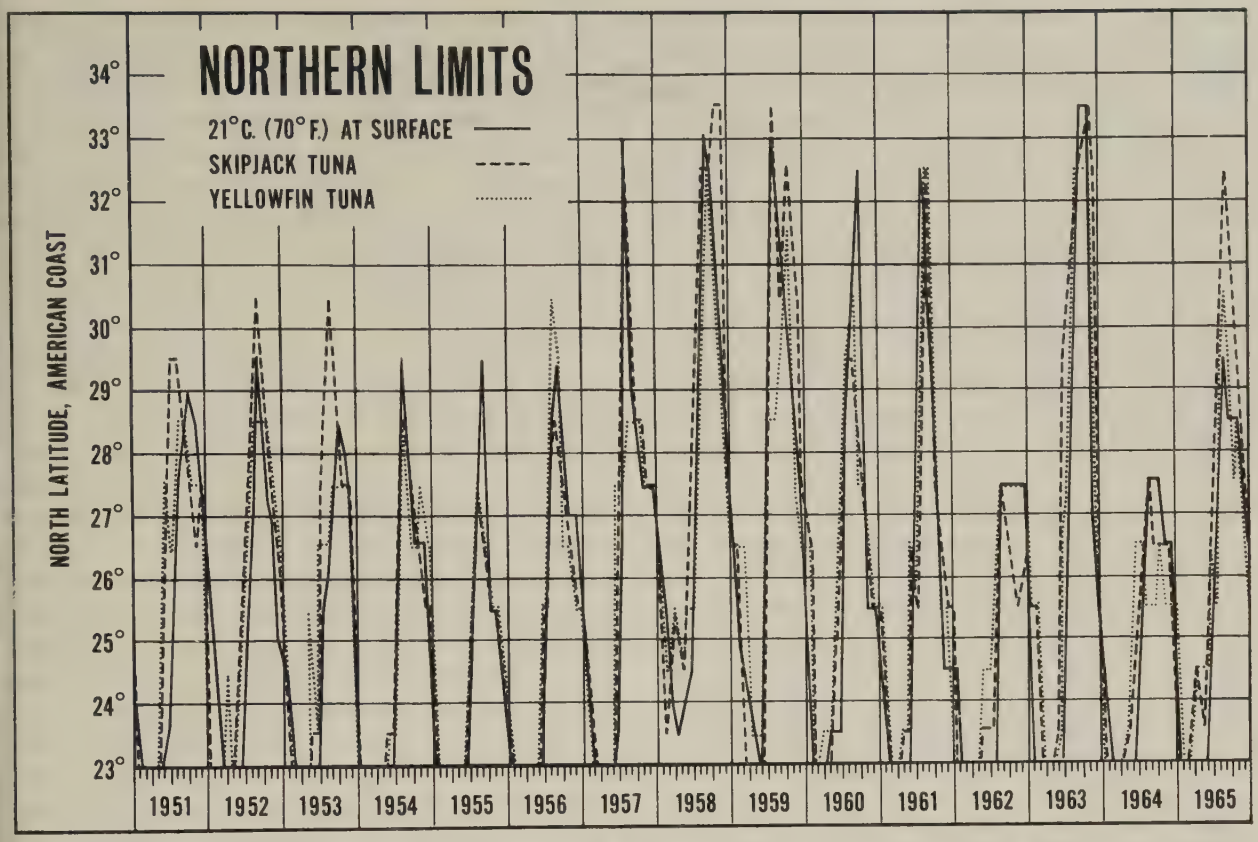

FIGURE 1.—Changes in latitudinal position of the 21° C. surface isotherm and of the northern limits of commercially caught yellowfin and skipjack tunas off the coast of Baja California and California, 1951–65.

when suitable food is abundant in those waters, but do occur in waters of surface temperature at and above 20° C., provided suitable food is abundant. "Suitable food" was defined as pelagic red crab, and "abundant" was defined as a concentration at or above 40 ml. displacement volume per 1,000 m.^{3} of water. The specified temperature, prey species, and concentration of prey are explained below.

The cruises were intended also to identify environmental properties that determine the distribution of the red crab, which is important in the diet of other commercial fishes as well as yellowfin and skipjack tunas (Boyd, 1967). Nothing was known about these properties except that temperature was not one of them (Longhurst, 1967). I thought that the properties would include standing stock of phytoplankton or of zooplankton, depending upon whether the red crab was predominantly herbivorous or carnivorous in the area studied; in the outcome it proved, as expected, to be predominantly herbivorous (Longhurst et al., 1967). Further, the cruises were intended to investigate possible relations between the tuna-connected properties—temperature, prey, food of the prey—and physical features of the environment such as upwellings and fronts. The results of those studies are included in this paper.

The range-limiting temperature was specified in the hypothesis as 20° C. for both species of tuna, but some deviation from it was expected. Range-limiting temperatures for yellowfin and skipjack have been discussed by Uda (1957), Blackburn and associates (1962), Laevastu and Rosa (1963), Broadhead and Barrett (1964), Blackburn (1965), and others. It is evident from these papers that successful commercial fishing, which requires a fairly high concentration of the fish, seldom occurs at temperatures below 20° C. for yellowfin tuna or below 19° C. for skipjack tuna. Both species can occur in waters as cool as 15° C. in some parts of the world, however. In the eastern Pacific the limiting temperature appears to be nearly always close to 20° C. for commercial concentrations of both species. Blackburn and associates (1962)

found that the northern range limits of the species agreed in position with the 21° C. (70° F.) surface isotherm at almost any time. Broadhead and Barrett (1964) showed a similar agreement of both northern and southern range limits with the 20° C. (68° F.) surface isotherm.

Figure 1 shows the kind of data that Blackburn and associates (1962) presented for the period 1951–59, together with similar data for 1960–65. It gives the approximate latitudinal position, in each month of 1951–65, of the northern limit of commercially caught yellowfin tuna, the northern limit of commercially caught skipjack tuna, and the 21° C. surface isotherm. The latitudes shown are those along the entire west coast of Baja California and the southern part of the coast of California. Tuna range limits are based on IATTC catch data that are grouped by 1° squares. They have been graphed at the midpoint of the 1° range of latitude at which the most northern commercial catch (regardless of its amount) was made during the month. Temperatures for 1951–59 are from the series of monthly temperature charts published by Eber, Saur, and Sette (1968), except for August 1952 when CalCOFI cruise data showed a more northward penetration of the 21° C. isotherm. Temperatures for 1960–65 are from monthly temperature charts published by the BCF (Bureau of Commercial Fisheries) Biological Laboratory, San Diego, Calif. Because the BCF temperature data were contoured in intervals of 5° F., including 70° F. (21° C.), it was more convenient to compare tuna limits with 21° C. than with 20° C.

As mentioned previously, figure 1 illustrates the seasonal movement of yellowfin and skipjack tunas along the west coast of Baja California (and in some years, California). It is not a spawning migration for either species (Orange, 1961; Klawe, 1963). The tunas appear west of the southern tip of Baja California (lat. 23° N.) in late spring or early summer, extend their ranges northward during the summer, contract their ranges southward during the autumn and early winter, and leave the area (except in 1958) during the late winter and early spring. The 21° C. surface isotherm changes position in the same way. The positions of the isotherm and the range limits vary from year to year in the same month, but they generally agree closely with one another in any particular month. It is because of this agreement that I think temperature determines the range limits. Figure 1 shows a few disagreements which could have resulted from temperature data or tuna data that were unrepresentative of conditions within a month. The two kinds of data were not collected together. All temperature data apply to the sea surface or the upper 10 m., where yellowfin and skipjack tunas are generally seen and caught.

The range of skipjack tuna appears to be limited also by a high temperature, about 28° C., and the same temperature or a higher one may possibly limit the range of yellowfin tuna (Blackburn, 1965, and references there). Such temperatures seldom occur in extensive areas off western Baja California, however.

Nothing indicates that temperature plays any direct part in determining the patchy distribution of the tunas within their range limits (Blackburn, 1965). According to the hypothesis being tested, food supply is responsible for this aspect of the distribution. The principal food organism of tropical tunas off western Baja California is red crab, as mentioned above. Alverson (1963) sorted stomach contents of 567 yellowfin and 151 skipjack tunas taken off the west coast of Baja California and the coast of California. The composition of the stomach contents of yellowfin tuna by volume was 78 percent red crab, 10 percent northern anchovy, *Engraulis mordax*, and 12 percent other animals (euphausiids absent). The composition of the skipjack tuna stomach contents was 37 percent red crab, 28 percent northern anchovy, 19 percent euphausiids, and 16 percent other animals. Northern anchovies are much more abundant off California and northern Baja California than off southern Baja California, however (Baxter, 1967; Ahlstrom, 1967); in the latter area red crabs are, therefore, probably a larger component of the tunas' diets than Alverson showed. Northern anchovies were very seldom taken on the cruises described in this paper, probably because they were not common in the area. Euphausiids were taken on these cruises, but it was decided not to attempt to study their distribution in relation to that of the tunas, for the following reasons. Euphausiids are more difficult to sort and measure volumetrically than red crabs are; they are not routinely catchable or observable by some of the methods

TABLE 1.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10³m.³ of water strained, on cruise TO–64–1*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10³m.³			*Ml./10³m.³*			*Ml./10³ m.³*
3	M	32	24	Z	7	53	Z	865
4	Z	69	26	Z	62	54	Z	310
5	Z	34	27	Z	7	55	Z	35
7	Z	7	28	Z	18	56	Z	2,364
9	S	>40	29	M	7	57	Z	1,092
0	M,Z	>40	30	Z	26	58	Z	1,446
1	Z	17	34	Z,M	68	59	Z	614
2	Z	123	35	Z	6	60	Z	225
5	Z	7	36	Z	176	61	Z	108
6	M,Z	72	48	M	46	62	Z	492
7	Z	386	49	Z	5	63	Z	284
8	Z	316	50	Z	43	64	Z	1,142
9	Z	13	51	Z	6	65	Z	80
3	M,Z	36	52	Z	198	66	Z	3,437

that were useful with red crabs (high-speed net catches, and observations at the sea surface); and yellowfin tuna do not eat them. In any event, northern anchovies and some euphausiids are facultatively herbivorous like red crabs and might be expected to have a similar distribution.

I decided to distinguish between concentrations of red crabs that were greater or less than 40 ml./1,000 m.³, as mentioned above. Concentrations above zero ranged from 0.1 to 5,238 ml./1,000 m.³ (tables 1–6), with median 36 ml./1,000 m.³ It is implicit in the hypothesis being tested that tunas, which are highly mobile, encounter and aggregate around the highest concentrations of food in any area which they enter. It was, therefore, desirable, on the one hand, to use some value at least as high as the median to distinguish high concentrations from low. On the other hand, the frequencies at successive intervals of concentration declined sharply above the median, to the extent that charting would have been difficult if a value appreciably over 100 ml./1,000 m.³ had been used. Trial made it evident that the property charts presented later, and the conclusions of the study, were much the same at a value of 40 (just above the median) and at 100 ml./1,000 m.³ Therefore, the former value, which made more data available for drawing isograms of abundance of red crabs on the charts, was chosen.

MATERIAL AND METHODS

The following sections give information about the cruises and stations from which data were obtained; the methods used for measuring surface temperature, surface chlorophyll *a*, and concentration of red crabs; and the kinds and sources of contemporaneous data on tunas.

CRUISES AND STATIONS

The oceanographic data for this study were obtained in six cruises—one made in 1959, which generated the hypothesis mentioned above, and five made in 1964–66. The area of study was restricted to south of lat. 28° N., where the tunas (fig. 1) and red crabs (Longhurst, 1967) occur each year; these species appear farther north in some years, but not in all. Figure 2 identifies localities and topographic features to which I refer in this paper. The principal banks (underwater elevations of the bottom) within and beyond the 100-fathom (183–m.) line, and the small islands known as Alijos Rocks, are shown. Tuna fishermen consider that these features represent good fishing areas, a matter which is discussed later.

The tracks and station positions for the six cruises are shown in figures 3, 5, 7, 9, 11, and 13, which appear in later sections of this report. They were based on the CalCOFI basic station plan (since 1950), and most of the stations can be identified easily with CalCOFI station positions (Anonymous, 1963), although they have not been numbered in the CalCOFI way. Two of the cruises were devoted entirely to occupying a series of CalCOFI stations (figs. 7 and 9). On each of the other four cruises (figs. 3, 5, 11, and 13) a series of CalCOFI stations was occupied first (part 1 of the cruise, terminating in the southern part of the area) and the ship then returned northward by a different route, occupying special stations in areas of particular interest (part 2 of the cruise). The

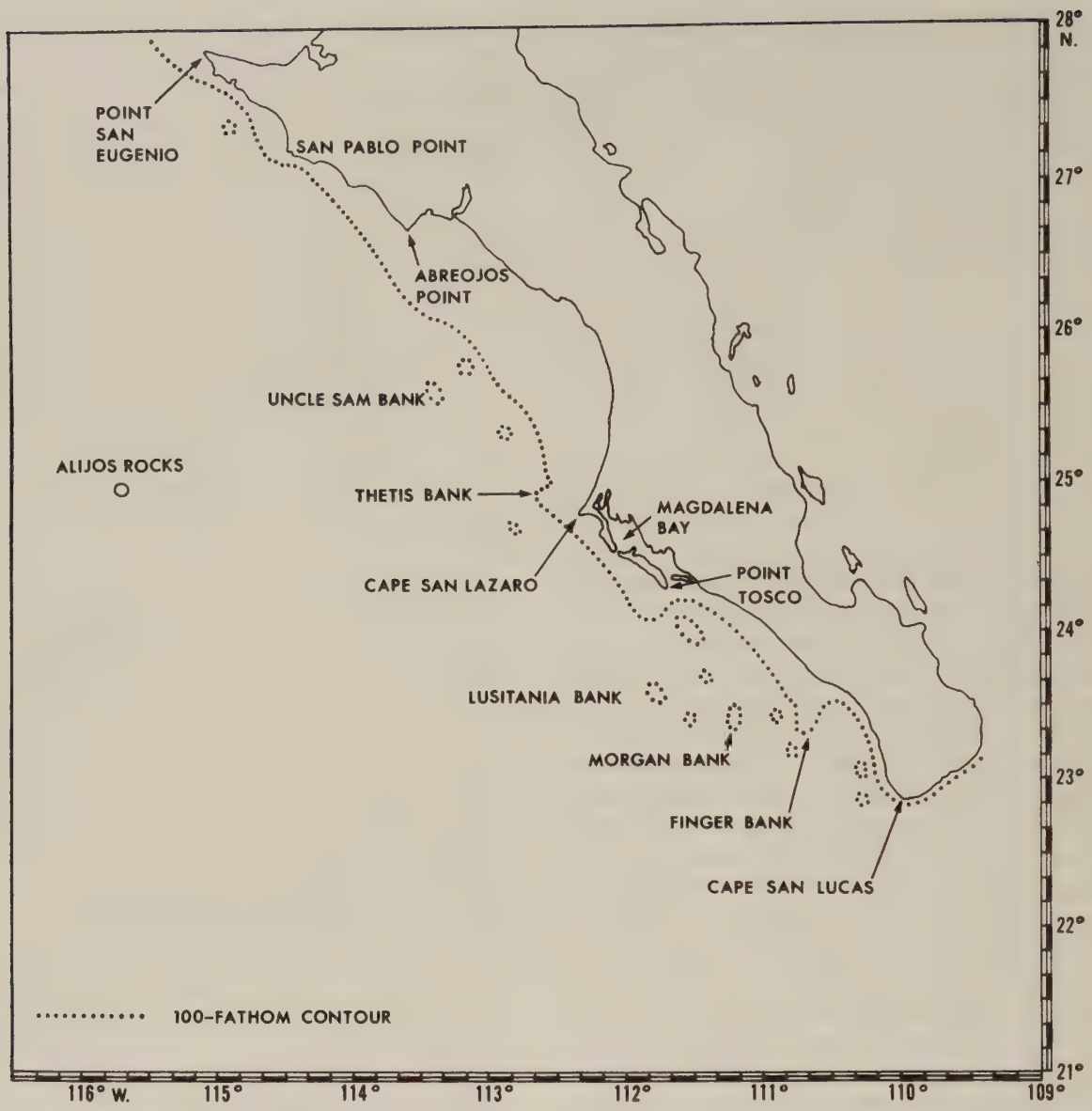

FIGURE 2.—Localities and topographic features referred to in the paper.

figures identify the stations that were occupied close to local noon and midnight so as to indicate approximately which portions of the track were covered in daylight and which in darkness.

Although many physical, chemical, and biological properties were measured at several depths at most stations, this paper is concerned only with data on surface temperature, standing stock of phytoplankton, pelagic crabs, and tunas, for reasons given earlier. The stock of phytoplankton was measured as concentration of chlorophyll *a*, and in this paper I discuss only surface concentrations, which were measured much more often than concentrations at other levels.

SURFACE TEMPERATURE

The term "surface temperature" is used for convenience, for the temperature data in this paper are not precisely from the sea surface. Mainly they are from 10 m. below the surface, where temperature was measured at almost every station with a reversing thermometer. Temperatures read from bucket thermometers, bathythermographs, and thermographs that recorded sea-water injection

temperatures aboard vessels were used in charting isotherms between station positions. The data for cruises TO–59–2 (considered as part of CalCOFI cruise 5908), 6608, TO–64–1, and TO–64–2 have been published (Scripps Institution of Oceanography, 1961, 1968, 1969). The data for cruises TO–65–1 and TO–66–1 are available from the Scripps Institution of Oceanography.

SURFACE CHLOROPHYLL *A*

On cruise TO–59–2, concentrations of chlorophyll *a* were determined by spectrophotometric measurement of optical density of acetone extracts by use of the equations of Richards with Thompson (1952). These data have been published (Blackburn, Griffiths, Holmes, and Thomas, 1962). On cruises TO–64–1 and TO–64–2, concentrations were determined by measuring the fluorescence of acetone extracts (Holm-Hansen, Lorenzen, Holmes, and Strickland, 1965; Lorenzen, 1966). The data have been published (Scripps Institution of Oceanography, 1969). On the other three cruises, determinations were made by measuring the fluorescence of acetone extracts or in vivo suspensions (Lorenzen, 1966) or both. The data for these cruises are available at the Scripps Institution of Oceanography. All available surface measurements were used in this study, irrespective of the time of day or night at which the material was collected. Concentrations are given in mg./m.^{3}

PELAGIC RED CRABS

The pelagic red crab was collected or observed and its concentration in the water estimated in several ways. Tables 1–6 list stations and localities between stations where red crabs were collected or observed on the six cruises and give the estimated concentrations in milliliters (displacement volume) /1,000 m.^{3} These data refer to adults and juveniles (postlarvae), but not larvae.

One method of collection (M in tables 1–6) was the standard micronekton net haul, which was made usually once each night. The net was the 1.5-m. (5-foot) net described by Blackburn (1968); it was hauled obliquely at a ship speed of 5 knots (9.3 km./hour). On cruises TO–59–2, TO–65–1, and TO–66–1, the hauls were made to a depth of about 90 m. with 350 m. of wire. On cruises TO–64–1 and TO–64–2 they were made to about 140 m. with 500 m. of wire. Wire was paid out at speeds of 20 to 30 m./minute and retrieved at speeds of 10 to 15 m./minute. This method was not used on cruise 6608; other methods, mentioned below, were employed on that cruise. The volume of water strained on each haul was estimated from the distance traversed in meters, the mouth area of the net in square meters, and an empirical filtration coefficient, 0.76 (Blackburn, 1968). Crab volumes were measured directly.

Another method (Z in tables 1–6) was the standard zooplankton net haul with the CalCOFI 1-m. net, which was usually made at each station. These hauls were made obliquely to a depth of about 140 m. at a ship speed of less than 2 knots (3.7 km./hour). Thrailkill (1956) described the net and hauling procedure. A flowmeter measured the volume of water strained on each haul. Volumes of red crabs were measured directly for cruises TO–64–1, TO–64–2, and TO–65–1. For the other three cruises the volumes were estimated from counts of crabs, using an empirical average volume of 3.0 ml. per crab, or 1.0 ml. per crab if they were recorded as small. Some crabs probably avoided these slowly moving nets, even at night. At 46 night stations both standard micronekton hauls and standard zooplankton hauls were made and red crabs collected. Volumes per 1,000 m.^{3} were equal in the two hauls at 3 stations, greater in the micronekton hauls at 31 stations (including 18 when the zooplankton haul was negative), and greater in the zooplankton haul at 12 stations (including one with a negative micronekton haul).

A third method (H in tables 1–6) was the high-speed micronekton net haul described by Blackburn (1968). This net is hauled horizontally at about 10 m. below the surface at the ordinary cruising speed of the ship. Such hauls were made, usually at night, on all cruises except TO–64–1. Their duration was from 2 to 3 hours on cruise TO–59–2, from ½ to 1½ hours on cruise TO–64–2, and 1 hour on other cruises. The volume of water strained was estimated from the distance traversed, the mouth area of the net, and an empirical filtration coefficient, 0.94 (Blackburn, 1968). Crab volumes were measured directly. I showed earlier (Blackburn, 1968) and found again in this study that volumes per 1,000 m.^{3} from these hauls average much smaller than those from standard micronekton hauls made at about the same time and place; the ratio, high-speed net volume/standard

micronekton net volume, is of the order 1 : 10. The reasons are unknown; possibly red crabs are scarcer in the upper 10 m. than at greater depths, or they may tend to avoid a fast-moving ship. The concentrations shown for this method in tables 1–6 have all been multiplied by 10 to make them broadly comparable with those from the other hauls.

The remaining sources of information about red crabs were sightings of aggregations at the sea surface and occurrences in the stomachs of predators that were captured from the ship. The concentration for each sighting was obviously over 40 ml./1,000 m.^{3} and is listed accordingly (see S in tables 1–6). On four occasions the stomachs of predators contained crabs. The predators were yellowfin tuna, dolphin, *Coryphaena hippurus*, and an unidentified turtle. Three of these occurrences were represented by only one predator individual; it was not then safe to assume that red crabs occurred at a concentration over 40 ml./1,000 m.^{3} In the other occurrence, three predator individuals (yellowfin tuna) containing red crabs were captured and many others seen; here it was reasonable to assume that a high concentration of red crabs was available (see P in table 5).

For stations at which two or more estimates of concentration were available, the highest one was listed in tables 1–6. In charting the isogram of 40 ml./1,000 m.^{3} concentration for each cruise, I used the data of tables 1–6, together with the zero concentrations recorded for the remaining stations. In view of the opinion of Boyd (1967) and Longhurst (1967) that red crabs make diurnal vertical migrations, I occasionally ignored estimates of low or zero concentrations based upon daytime catches or observations when other evidence suggested the probability of high concentrations in the area—for instance when surface chlorophyll *a* was high, and high concentrations of crabs were encountered during one or both of the adjacent nights. An additional justification for this procedure is that most of the daytime information was obtained from zooplankton hauls, which frequently yield low estimates of concentration as shown above. On the other hand, if a series of night observations all yielded low estimates of concentration I concluded definitely that red crabs were not abundant in the area examined, whatever the other circumstances were; I sometimes ignored an occasional low concentration in a series of high ones obtained during the same night.

Stations 60–66 of cruise TO–64–1 were occupied very close to each other, in an area of about 5 nautical miles (9 km.) radius, during a period of about 3 days. The odd-numbered stations were occupied about noon, the even-numbered stations about midnight. Table 1 shows the crab concentrations measured in zooplankton hauls at these stations which were all much higher than 40 ml./1,000 m.^{3} Concentrations were lower at noon than at midnight, as expected. Concentrations in consecutive hauls differed by a factor of about three in both the noon and midnight series. I have found similar differences for other kinds of organisms in noon and midnight series of micronekton hauls that were closely adjacent in space and time (Blackburn, 1968). Concentrations of red crabs estimated from single net hauls might, therefore, differ by a factor up to three from concentrations actually present in the water. I tried to allow for this possibility in charting the isogram of 40 ml./1,000 m.^{3} for each cruise.

TUNAS

Data on the recorded occurrence of yellowfin and skipjack tunas were obtained from IATTC, which has such data in various forms, one of which gives average catch per unit of fishing effort by species, by fishing method (live-bait and purse-seine), location by 1° squares, and by months. Such information had been very useful in previous work on tuna ecology in the Gulf of Tehuantepec (Blackburn, 1963) but was rather unsatisfactory for this study. The isograms of temperature, chlorophyll *a*, and red crabs intersected the parallels and meridians in a way that was frequently very complicated (e.g., fig. 6), and it was evident that their position did not always remain unchanged for the whole of the calendar month in which they were observed.

I used IATTC data on tuna occurrences that had definite dates and positions. Figures 4, 6, 8, 10, 12, and 14 (see later sections) show these occurrences separately for each species and for mixed catches of the two species. They refer either to the whole period when the ship was in the area of the charts or to some part of that period, as explained later for each cruise. The original data were available from baitboats and purse seiners separately, but the distributions of tuna from these two

sources were generally similar and are not distinguished in this paper. Data were available on the amounts of tuna captured at each of the charted positions, but they are not given here because size of catch is not necessarily a measure of abundance. Catch per unit of fishing effort can be considered as a measure of abundance, but it would be difficult to establish the amount of effort expended at each of the individual points shown on the charts. For this study, any commercial catch of tuna indicates an aggregation of the fish, and the main interest lies in the general distribution of the aggregations.

In areas where no occurrences are shown, there was either no significant fishing effort (hence tuna distribution unknown) or no fish, at the period of the cruise. Data showing absence of fish are few; they refer to combinations of 1° squares and months in which at least 5 boat-days of fishing effort yielded no catches. These examples of unproductive effort are mentioned later for the individual cruises.

A few catches and observations of yellowfin and skipjack tunas made from the oceanographic vessels have been included in the charts.

RESULTS OF INDIVIDUAL CRUISES

In the following sections, six cruises are discussed in the order that best represents the typical seasonal change during the period of the year when yellowfin and skipjack tunas occur west of Baja California. The distributions of surface temperature, surface chlorophyll *a*, red crabs, and tunas are described and explained for each cruise, with special reference to their relations with the seasonal cycle of coastal upwelling.

CRUISE TO–64–1

This cruise showed environmental conditions that are probably typical of the beginning of a yellowfin and skipjack tuna season off western Baja California (see fig. 1). Figure 3 shows the track and station positions, omitting individual positions of two clusters of stations that were occupied for special purposes. Figure 4 gives the essential features of the distributions of the properties previously discussed; this and similar figures show only selected isograms of surface temperature and surface chlorophyll *a*. The isotherms in figure 4 refer only to the temperature distribution on part 1 of the cruise, June 9–15, 1964. At the few stations that were re-occupied on part 2 of the cruise, temperatures averaged about 2° C. higher than on part 1. Figure 4 includes only those tuna occurrences that were recorded for the period June 9–15. The charted distributions of chlorophyll *a* and red crabs are based on all available data from the entire cruise, as they are also for the other cruises. The red crab data are given in table 1.

Along the Baja California coast below Point San Eugenio the coastal upwelling typically begins about April, is strong from April through June, and ceases about August (Reid, Roden, and Wyllie, 1958; Wyllie, 1961; Lynn, 1967). CalCOFI stations 123.37 and 143.26, which are the same as stations 2 and 18 in figure 3, are considered to be the centers of the two principal coastal upwelling areas (Lynn, 1967). These areas, one along the coast south of Point San Eugenio and the other south of Cape San Lazaro, are indicated by the 15° C. surface isotherm in figure 4. In the northern area, surface temperatures below 13° C. were recorded off San Pablo Point. The 16°, 17°, and 18° C. isotherms lie generally parallel to the coast, rather than in the wavy configurations described later for certain offshore isotherms on subsequent cruises. This parallel orientation appears to be normal in June (Anonymous, 1963).

Off Cape San Lucas a well-defined temperature front existed at the sea surface, oriented in much the same way as in May 1960 and April 1961 (Griffiths, 1963, 1965). Surface water below 17° C., in part below 16° C., lay in a narrow band just west of Cape San Lucas; it was probably upwelled farther north, where temperatures were similar. Eastward from this cold area along the south coast of the peninsula, surface temperatures rose to above 25° C. The 17° to 21° C. isotherms trended more or less to the southeast from Cape San Lucas, whereas the 22° to 25° C. isotherms trended parallel to the south coast of Baja California. The front, therefore, was very strong close to Cape San Lucas but split about 15 nautical miles (28 km.) offshore into two weaker parts. Some 60 miles (110 km.) southwest of Cape San Lucas, a tongue of water over 19° C., mostly over 20° C. (the two isotherms are close together), protruded north-

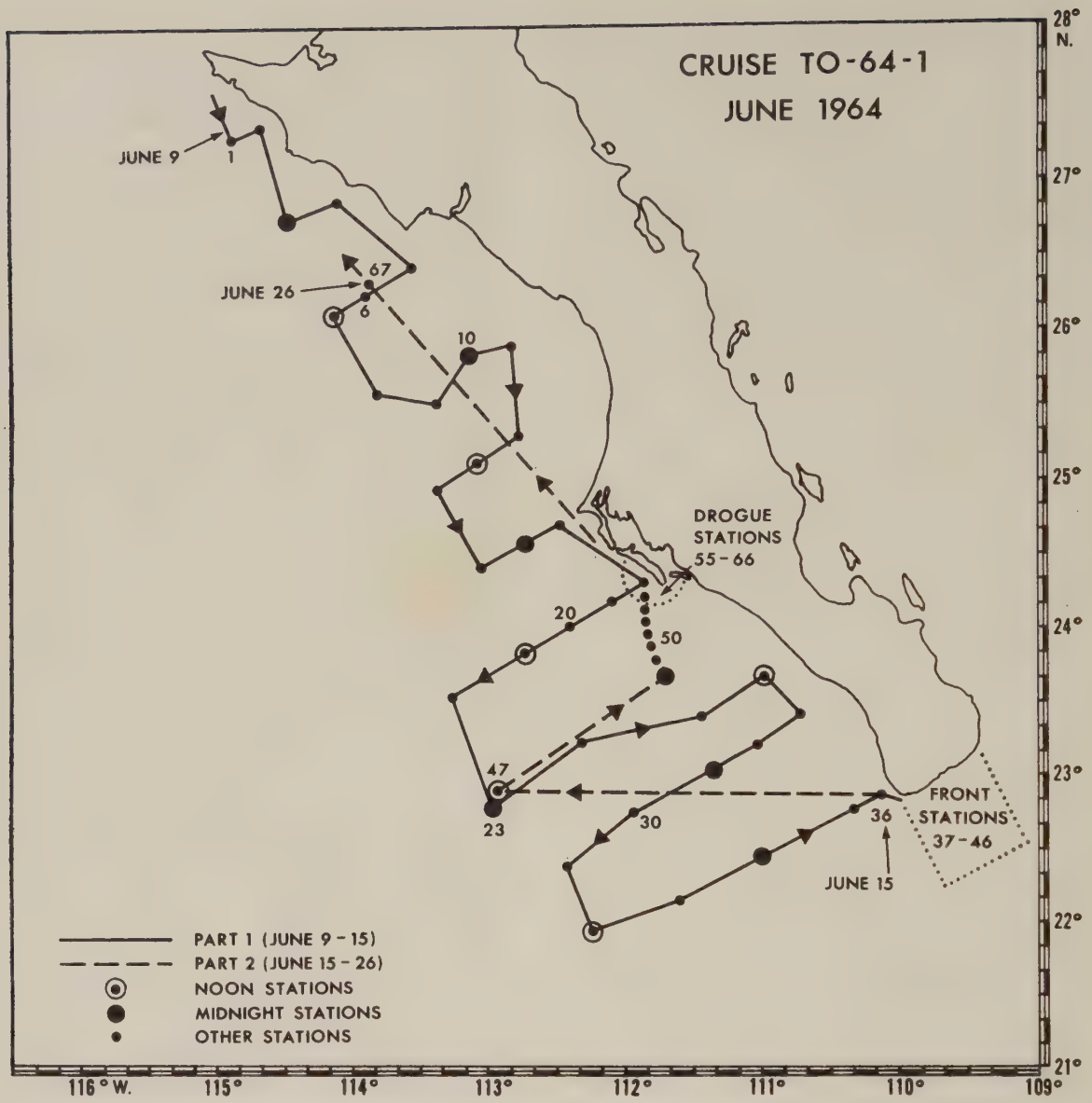

FIGURE 3.—Track and station positions for cruise TO–64–1.

ward into the cruise area. Such a warm tongue appears frequently at this time of year; for example, it occurred in June 1951 and June 1957 (Anonymous, 1963) and is shown in several of the BCF June temperature charts.

The standing stock of surface chlorophyll *a* was highest in the cold coastal water (upwelling or recently upwelled water), as expected. The 1.0 mg./m.^{3} isogram follows the coast and includes the principal upwelling areas, where some concentrations exceeded 6.0. Concentrations below 0.1 mg./m.^{3} were confined to the offshore region in the extreme south of the area (stations 31–34), and none of these values was below 0.06.

The area of red crab concentration over 40 ml./1,000 m.^{3} was large and broadly similar to that of chlorophyll *a* concentration over 1.0 mg./m.^{3} Thus, the red crab and its food supply had the same distribution. A separate small area of high concentration lay near Cape San Lucas, and another one farther offshore.

The tuna occurrences were in two groups in the southern part of the area—one (yellowfin tuna only) east of the front along the south coast of

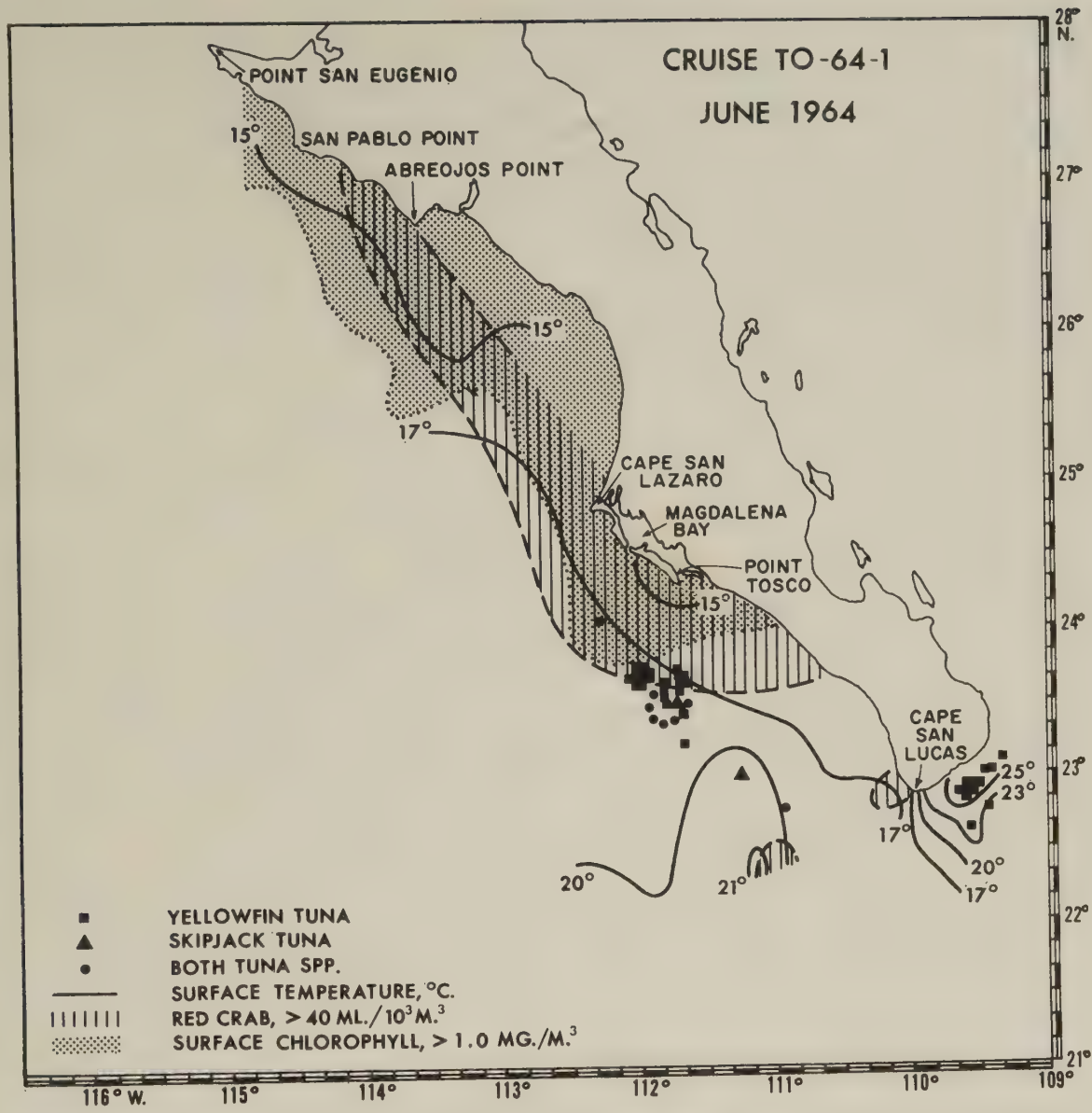

FIGURE 4.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO-64-1 and locations of contemporaneous tuna catches.

Baja California, and the other (both species) in and northwestward of the warm offshore tongue. Neither of these groups of tuna was in the area of highest concentration of food, although the second group reached the edge of it. In the front area virtually no red crabs were caught in three standard night micronekton hauls, and concentrations of all animals in these hauls (i.e., all potential tuna prey) ranged only from 9 to 16 ml./1,000 m.³ In the other tuna area concentrations of red crabs were 7 and 46 ml./1,000 m.³ at stations 29 and 48, and concentrations of all other micronekton were 14 and 10 ml./1,000 m.³ Some of the tuna aggregations in each of these areas were only about 25 nautical miles (46 km.) from a much richer food supply (over 100 ml./1,000 m.³ of red crabs—e.g., at station 52), but the fish would have had to encounter temperatures below 17° C. to reach it. Figure 4 shows that the tunas will tolerate 17° C. and suggests that lower temperatures are not acceptable.

A reasonable interpretation of figure 4 is that

both tuna species prefer some temperature at or over 20° C., will move into adjacent water as cool as 17° C. if food is more plentiful there, and will not enter water below 17° C. even if food is extremely abundant. If so, tuna will not round Cape San Lucas from the east as long as water under 17° C., and perhaps under 20° C., remains there; data from Griffiths (1963) indicated that 20° C. was the limiting temperature in May 1960. Under those circumstances their entry into the area west of Baja California will be by the offshore tongue of warm water, as suggested by figure 4. The area enclosed by the offshore 20° C. isotherm in figure 4 was well occupied by both species in the second half of June and the first half of July, although there were still no records of tuna caught between that area and the coast (between long. 110° and 111° W.). Tuna were not recorded in the latter area until the second half of July, when they suddenly became widespread; these fish were all yellowfin tuna, and probably the same aggregations as shown to the east of the front in figure 4. Probably the 20° C. isotherm moved northward from Cape San Lucas about mid-July and permitted the yellowfin tuna to round Cape San Lucas; this isotherm was located at about lat. 25° N. during the last 10 days of July (Scripps Institution of Oceanography, 1966). Thus, tuna appear to follow two pathways from the tropics into the area west of Baja California at the beginning of a tuna season, both determined by the distribution of surface temperature. One is from the east around Cape San Lucas, and the other is from the south. The former is mainly for yellowfin tuna, and the latter is for both species; skipjack tuna are much less common than yellowfin tuna to the east of the meridian of Cape San Lucas in most years (Joseph and Calkins, 1969).

Cruise TO–64–1 was the only one of this series in which tuna occurred at temperatures substantially lower than 20° C. They probably can tolerate temperatures down to 17° C. to obtain a larger food supply, as indicated above. Lee (1952) found that cod will enter waters over 2° colder than those in which they usually occur if food is plentiful. On cruise TO–64–1 only one small area had more than 40 ml./1,000 m.^{3} of red crabs in water at 20° C. or over (station 34, with 68 ml./1,000 m.^{3}). On all the later cruises, such areas were extensive and the concentrations of red crabs in them were generally over 100 ml./1,000 m.^{3}

Several tuna boats were fishing off the south coast of Baja California at the time the front was surveyed, and their operations were watched to see if their fishing success bore any relation to the position of the front. The only obvious relation was that they worked mainly to the east or north of the front and occasionally on its warm edge. They were probably avoiding water under about 20° C., and the front itself, as distinct from the limiting isotherms located in it, seemed to have no effect.

Various authors have suggested that tunas may aggregate in fronts in response to aggregations of prey organisms. Griffiths (1963, 1965) found that some kinds of zooplankton were more abundant in the middle of the Cape San Lucas front than on either side of it, but, on the other hand, micronekton (potential tuna forage) was most abundant on the warm side. On cruise TO–64–1 micronekton hauls were again made on both sides of the front and in the middle, all on the same night; the highest concentration was on the warm side, as in Griffiths' series, but all three concentrations were similar (16.3 ml./1,000 m.^{3} warm side; 9.1, middle; 11.8, cold side).

All the foregoing observations were made in the part of the front that is oriented parallel to the south coast of Baja California. Another series of seven micronekton hauls, made across the stronger part of the front near Cape San Lucas on cruise TO–64–1, showed highest concentrations in the upwelled water on the cold side. The evidence, therefore, does not support the idea of a concentration of tuna forage in the Cape San Lucas front. This front may have no special attraction for tunas and is probably avoided by them when unsuitably cold water occurs in it.

CRUISE TO–64–2

The results of this cruise, which was made in August of a rather cold year (see fig. 1), are probably typical of conditions in the early part of the tuna season, including July, when the fish rapidly expand their range northward. Figures 5 and 6 show cruise coverage and property distributions. The isotherms in figure 6 refer to the temperature distribution on part 1 of the cruise, August 5–16, 1964. At the few stations that were re-

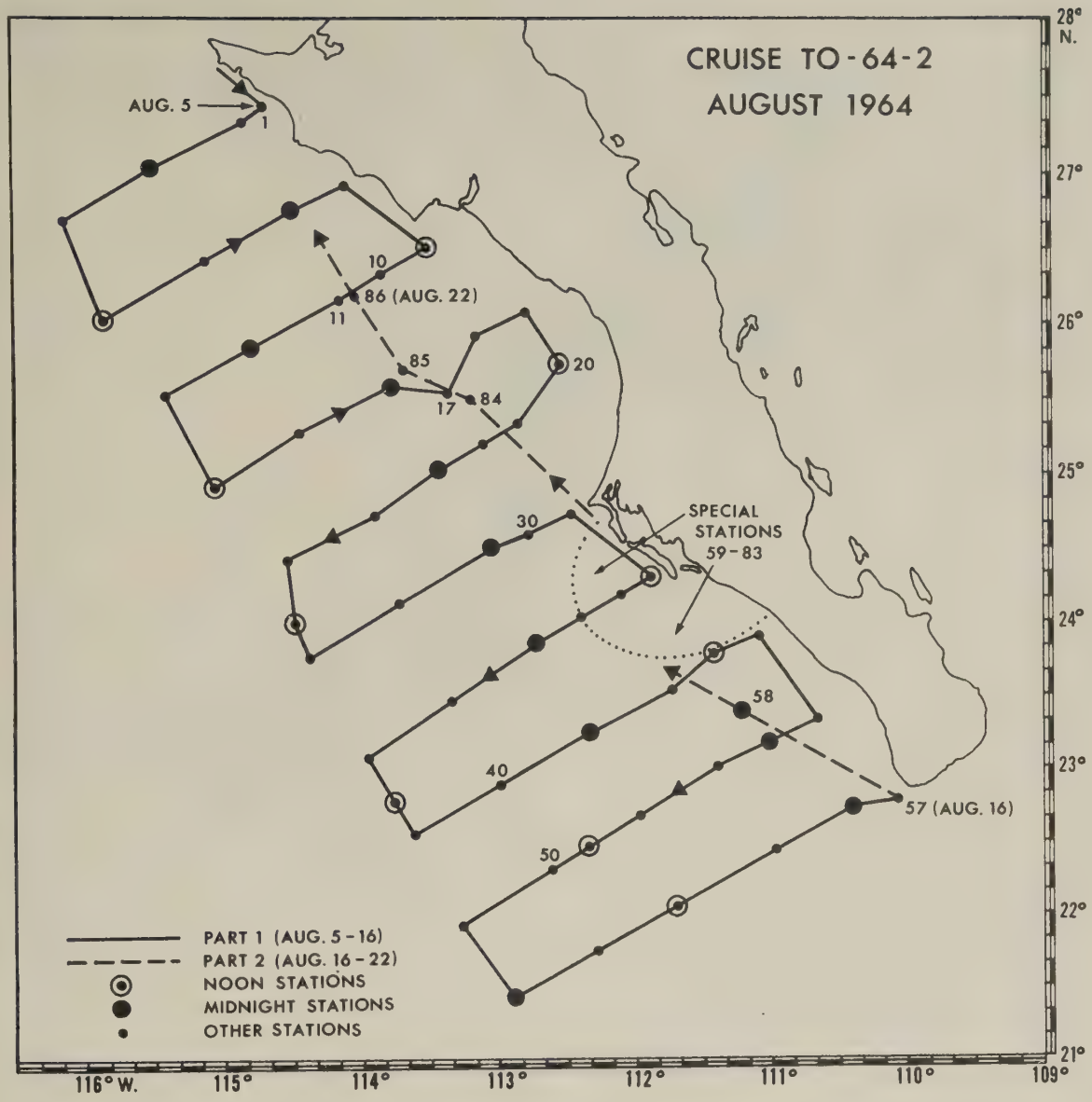

FIGURE 5.—Track and station positions for cruise TO–64–2.

occupied on part 2 of the cruise, temperatures were about the same as on part 1 except on August 21 and 22, when they were about 2° C. higher. Figure 6 includes only those tuna occurrences that were recorded for the period August 5–20. The red crab data are given in table 2.

Detailed surface temperature charts for the area in July and August show in most years a different configuration of isotherms from that found in June (Anonymous, 1963). Instead of lying more or less parallel to the coast, the isotherms become wavy; tongues of relatively cool water extend away from the coast, separated from each other by tongues of relatively warm water extending toward the coast. Figure 6 shows this situation very well; cold tongues run offshore from the two principal upwelling areas identified on cruise TO–64–1, and the northern area gives rise to at least two tongues. This distribution is probably caused by the eddies that characteristically appear about July and August (Wyllie, 1966). In figure 6 and later figures, the isotherms selected for charting always included those which showed the tongues, if present, in most detail. Temperatures under 20°

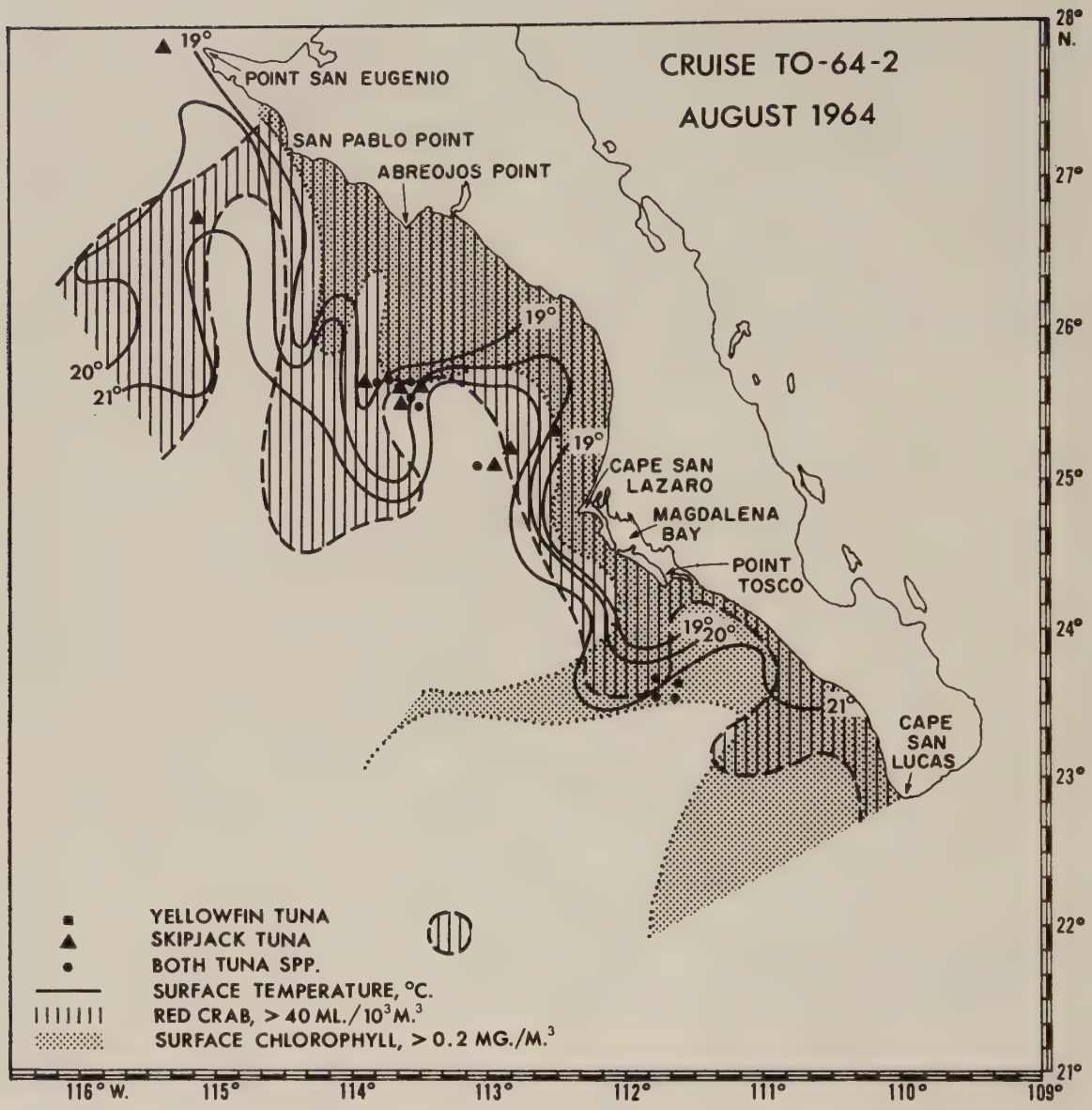

FIGURE 6.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO–64–2 and locations of contemporaneous tuna catches.

occurred almost all along the coast on cruise TO–64–2; minima, at stations 1, 8, and 31, were between 15° and 16° C., and maxima, at stations 53 and 54, were between 26° and 27° C.

Concentrations of surface chlorophyll *a* ranged from 6.4 to 0.01 mg./m.³ Their generally much lower values than on cruise TO–64–1 reflect some decay in the upwelling regime. Only station 32 had a concentration above 1.0 mg./m.³ The isogram of 0.2 mg./m.³ in figure 6 follows rather closely the edge of the cool water, except in the extreme northwestern part of the area covered. It protrudes farther offshore between lat. 23° and 24° N. than the corresponding protrusion of the isotherms. The 0.1 mg./m.³ isogram (not shown) follows it closely in most areas.

The position of the isogram showing 40 ml./1,000 m.³ of red crabs is close to the 21° C. isotherm and the 0.2 isogram of chlorophyll *a*, except in the northwestern part of the area (fig. 6). In general, relatively high standing stocks of red crabs and

TABLE 2.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10 ^{3}m.^{3} of water strained, on cruise TO–64–2*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10^3 m.^{3}			*Ml./10^3 m.^{3}*			*Ml./10^3 m.^{3}*
4–5	H	520	30–31	H	143	58–59	H	165
7	Z,M	63	32	Z	531	60	S	>40
7–8	H	>40	34	Z	4	63	Z	103
12	Z,M	24	36	Z	13	64	Z	17
12–13	H	18	40	Z	11	65	Z	33
12–13	H	879	44	Z	9	69	Z	54
13	S	>40	45	S	>40	70	Z	9
16	M	1	46	M,Z	355	73	Z	9
16–17	H	190	50	Z	4	74	Z	7
17–18	H	333	51	Z	48	75	Z	13
17–18	H	18	51–52	H	3	76	Z	89
23	M	7	52	M,Z	37	77	Z	197
23–24	H	268	52–53	H	35	78	Z	26
23–24	H	>40	55	Z	6	79	Z	562
24	Z	11	56	M	1	80	Z	232
24–25	H	314	56–57	H	83	81	Z	101
27	Z	4	57	Z	13	(1)	M	>40
29	M	1	58	Z,M	5			

[1] Series of night surface hauls with the large micronekton net near Uncle Sam Bank.

chlorophyll *a* occurred together in the upwelling or in recently upwelled water.

The occurrences of tuna (both species) were on the edges of the area of high concentration of red crabs where surface temperatures were all between 22° and 18° C. No tuna were recorded in the large inshore areas where red crabs were equally or more abundant and temperatures were lower; the fish probably avoided these areas. One 1° square, bounded by lat. 26° and 27° N. and long. 114° and 115° W., had a significant amount of fishing effort (six boat-days) that yielded no tuna in the month of the cruise. According to figure 6, almost all of this area was either colder than 20° C. or had less than 40 ml./1,000 m.^{3} of red crabs; it is not surprising then that tuna were not found. Elsewhere, in areas where no occurrences are shown in figure 6, the distribution of yellowfin and skipjack tunas at the time of the cruise is not known. Tunas could have occurred along other parts of the edge of the cool, food-rich, water.

Figure 6 shows an isolated occurrence of abundant red crabs far offshore, where surface chlorophyll *a* was below 0.1 mg./m.^{3} and tuna distribution unknown. Such offshore distributions, which Boyd (1967) and Longhurst (1967) have reported previously, may represent individuals that the California Current has carried out of the coastal region.

CRUISE 6608

This CalCOFI cruise, made in August 1966, covered only part of the area of interest. The results represent conditions at a slightly later stage in the year than those for cruise TO–64–2. The CalCOFI stations have been given serial numbers as shown in figure 7. Figures 7 and 8 show cruise coverage and distributions of properties. The red crab data are given in table 3.

The surface isotherms (fig. 8), especially 23° C., show the same tonguelike distributions as before. Cool tongues ran offshore from areas which lie south of Point San Eugenio and Abreojos Point; here a small inshore belt of upwelling or upwelled water under 20° C. occurred. Warmer water lay on both sides of these tongues. Surface temperatures for the whole area were between 17° and 26° C.—very close to the range (16°–25° C.) in an average August (Anonymous, 1963).

Concentrations of surface chlorophyll *a* ranged from 2.0 to 0.03 mg./m.^{3}, but those over 1.0 mg./m.^{3} were confined to a small inshore area between Point San Eugenio and San Pablo Point. It was not possible to draw an isogram for 0.1 mg./m.^{3} with confidence, because observations were not made in some parts of the area. In general, concentrations below 0.1 mg./m.^{3} were in water over 23° C., outside the main cool tongue shown in figure 8, but some of them were in the small (eastern) cool tongue as well. All concentrations above 0.2 were in the cooler water, as expected. They are charted in figure 8 to show two areas, which may, however, have been joined, because observations were not made between them.

The sampling of red crabs on this cruise was

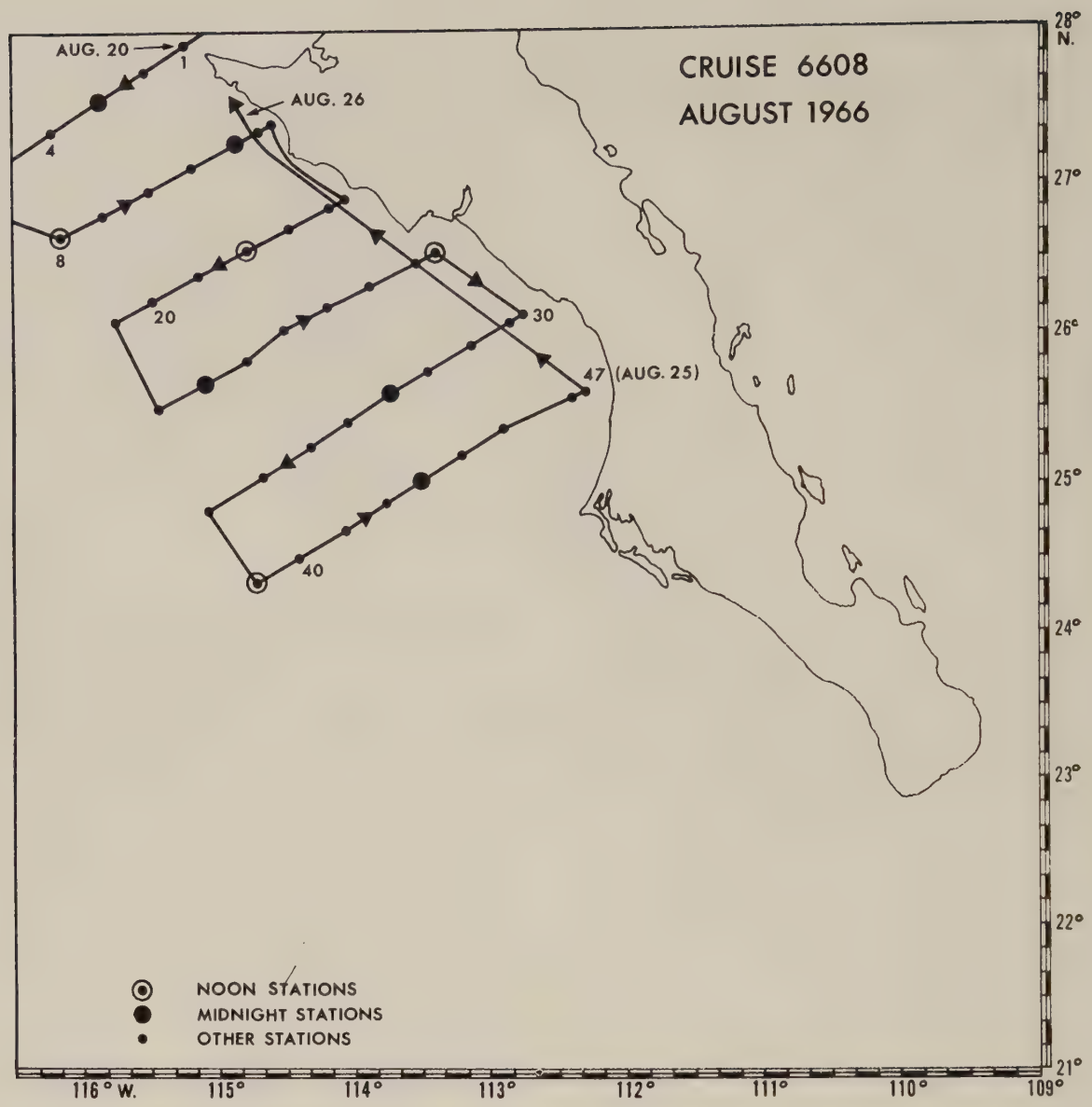

FIGURE 7.—Track and station positions for cruise 6608.

more restricted than on most of the other cruises because no standard micronekton hauls were made. Figure 8 shows four areas with concentrations over 40 ml./1,000 m.^{3} The northern area was in water which was cool and rich in chlorophyll *a* (over 0.2 mg./m.^{3}); the eastern area was partly in and partly adjacent to the same kind of water; the southwestern area was in and adjacent to a tongue of cool water, with chlorophyll *a* concentrations about 0.1 mg./m.^{3}; and the remaining small area was in warmer water where no chlorophyll data were obtained.

The data on tuna occurrence for the period of the cruise, August 20–26 (fig. 8) show a single record in the northern part of the area, located, like those on cruise TO–64–2, on the edge of an area that was rich in food but rather cold. The other records show a distribution of tuna right across one of the tongues of cool water, where temperatures were nevertheless high enough (over 20° C.) to permit the tuna to exploit the high concentration of red crabs; the tuna were located partly in and partly on the edge of this concentration of food. A significant amount of fishing

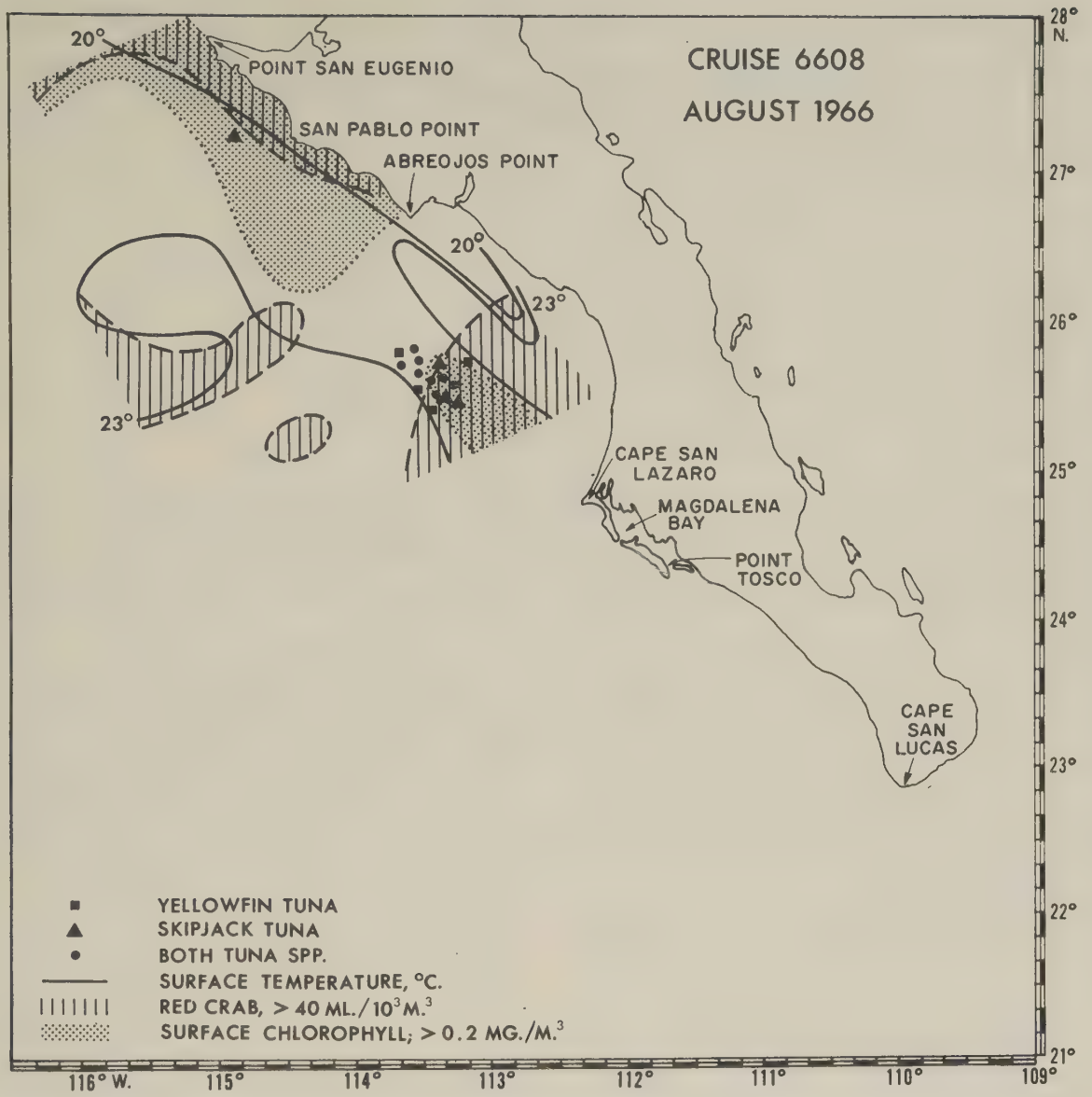

FIGURE 8.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise 6608 and locations of contemporaneous tuna catches.

effort (nine boat-days) in one 1° square, bounded by lat. 26° and 27° N. and long. 114° and 115° W., took no tuna in the month of the cruise. According to figure 8, nearly all of this area was either colder than 20° C. (the northeastern corner) or had less than 40 ml./1,000 m.³ of red crabs at the time of the cruise. It would not, therefore, be expected to contain many tuna. Elsewhere the distribution of tunas at the time of the cruise is not known. Fishing effort was not significant in the area of high concentration of red crabs in the southwestern part of the cruise area, where temperature and food were suitable for tunas.

CRUISE TO–59–2

This cruise, made August 16–29, 1959, was in a warm year (see fig. 1), and the results represent conditions at a later stage in the year than those for the previous cruise. The cruise started farther south than the others in this series; the area immediately to the north was covered at the same period by CalCOFI cruise 5908 which yielded

TABLE 3.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10 ^{3}m.^{3} of water strained, on cruise 6608*

[Letters under kind of observation signify: Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10^3 m.^{3}			*Ml./10^3 m.^{3}*			*Ml./10^3 m.^{3}*
1	Z	>40	23	Z	25	36	Z	113
1–2	H	>40	23–24	H	1,069	38	Z	6
2	Z	12	24	Z	7	41–42	H	17
5–6	H	392	24–25	H	334	43	Z	56
6	Z	13	25	S,Z	>40	43–44	H	426
7	Z	6	30	Z	28	44	S,Z	>40
14–15	H	1,353	31	S,Z	>40	45	Z	67
15	Z	13	31–32	H	818	45–46	H	468
16	Z	215	32	Z	20	46	Z	24
20	Z	7	32–33	H	12	(1)	H	5
21	Z	45	33–34	H	27	(1)	H	735
21–22	H	701	34	Z	14	(1)	H	1,762
22–23	H	1,044	35–36	H	58	(1)	H	14

[1] After station 47, on northbound track between lat. 26°30′ N. and 27°50′ N., at night.

temperature data (Scripps Institution of Oceanography, 1961), but no data on chlorophyll or red crabs. Cruise coverage and property distributions are shown in figures 9 and 10. Data on red crabs are given in table 4.

Surface temperatures were between 18° and 30° C. but the areas under 20° C. and over 28° C. were extremely restricted (fig. 10). The cold inshore region between Point San Eugenio and San Pablo Point probably represents upwelling at a very late stage. A large tongue or tongues of relatively cool water (less than 25° C.) ran offshore from the coastal upwelling area as shown for previous cruises. No such signs of relatively cool water were off Magdalena Bay, where upwelling probably ceases earlier than it does farther north.

Observations on surface chlorophyll *a* were fewer on this cruise than on the others. Concentrations were much lower than before—from 0.11 to 0.02 mg./m.^{3}, which is consistent with the indications of a further weakening of upwelling. Concentrations were at or above 0.1 mg./m.^{3} only at stations 20, 30, 37, 38, 41, and 42. The isogram of 0.05 mg./m.^{3} follows the 25° C. isotherm fairly well (fig. 10), so the offshore tongue of relatively cool water generally had a higher concentration of chlorophyll than the surrounding warmer water.

The area in which concentrations of red crabs exceeded 40 ml./1,000 m.^{3} was broadly congruent with the area of cool water and the area of highest surface chlorophyll. The isograms of these three properties tend to be displaced a little from each other, but otherwise they agree in considerable detail. There was an isolated patch of red-crab-rich water off Magdalena Bay; it was not cool, and chlorophyll was not sampled in this particular area.

About half of the tuna catches that were made at the time of the cruise were north of Abreojos Point, where data on chlorophyll and red crabs are lacking; temperatures were mostly over 20° C. The catches to the south of Abreojos Point all were from water over 20° C. and show the kind of association with chlorophyll and red crabs that was mentioned for cruise 6608. The tuna were not only on the edges of the biologically rich areas but in the cores of these areas as well. The areas of abundant forage, which on cruise TO–64–2 were too cold for tunas except at the edges, were warm enough for the fish to penetrate on this cruise. As before, tuna distribution was not determined (insignificant amount of fishing) in certain large areas, including some in which temperature and food conditions appeared highly suitable.

CRUISE TO–65–1

This cruise (figs. 11 and 12), which was in September 1965, represents a still later stage in the year, when the distribution of surface temperature gives no indication of any coastal upwelling. The lowest temperatures, between 20° and 21° C., were offshore and probably indicate California Current water. The highest temperatures were slightly over 28° C. Temperatures on part 2 of the cruise were about the same as on part 1. On CalCOFI cruise 6509, which extended into the northern part of the area near the end of cruise TO–65–1, sur-

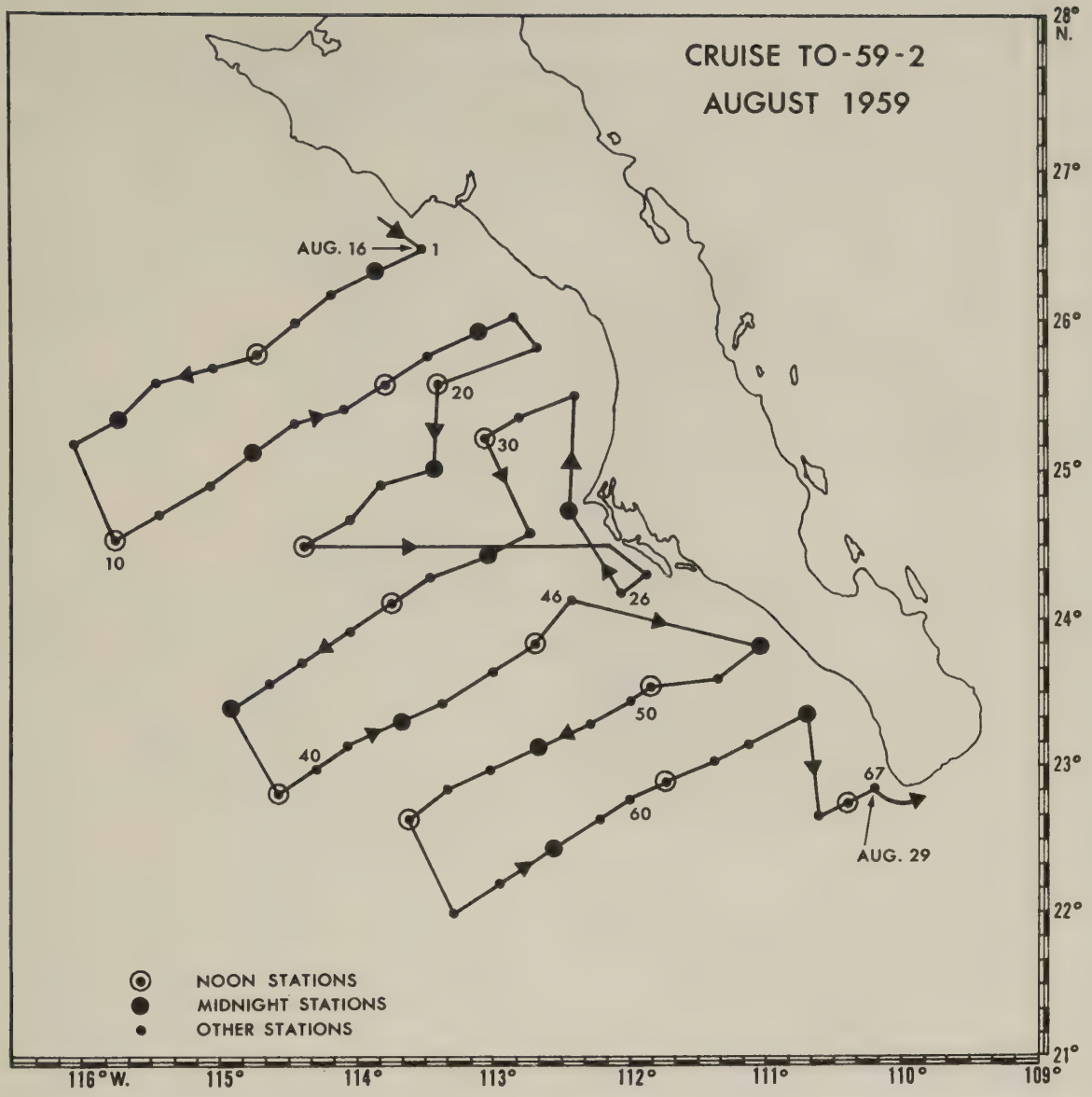

FIGURE 9.—Track and station positions for cruise TO–59–2.

face temperatures were about 1.5° C. lower in a few inshore localities, and elsewhere about the same as on TO–65–1 (Scripps Institution of Oceanography, 1967). Even these lower temperatures were over 20° C. and would not be expected to affect tuna distributions; therefore, all tuna occurrences for the whole period, September 8–25, 1965, have been given in figure 12. Data on red crab concentrations are given in table 5.

Surface chlorophyll *a* concentrations were all below 1.0 and ranged down to 0.02 mg./m.^{3}, although they were generally higher than on cruise TO–59–2. The 0.2 mg./m.^{3} isogram encloses the area of highest concentration, which is tonguelike and originates on the coast south of Point San Eugenio, as on previous cruises. It probably represents the biological result of a tongue of upwelled water which can no longer be distinguished from the surrounding water by its temperature. All stations inshore of this tongue and the following stations offshore had over 0.1 mg./m.^{3}: 4–6, 12, 13, 17, 23, 26–29, 32, and 36.

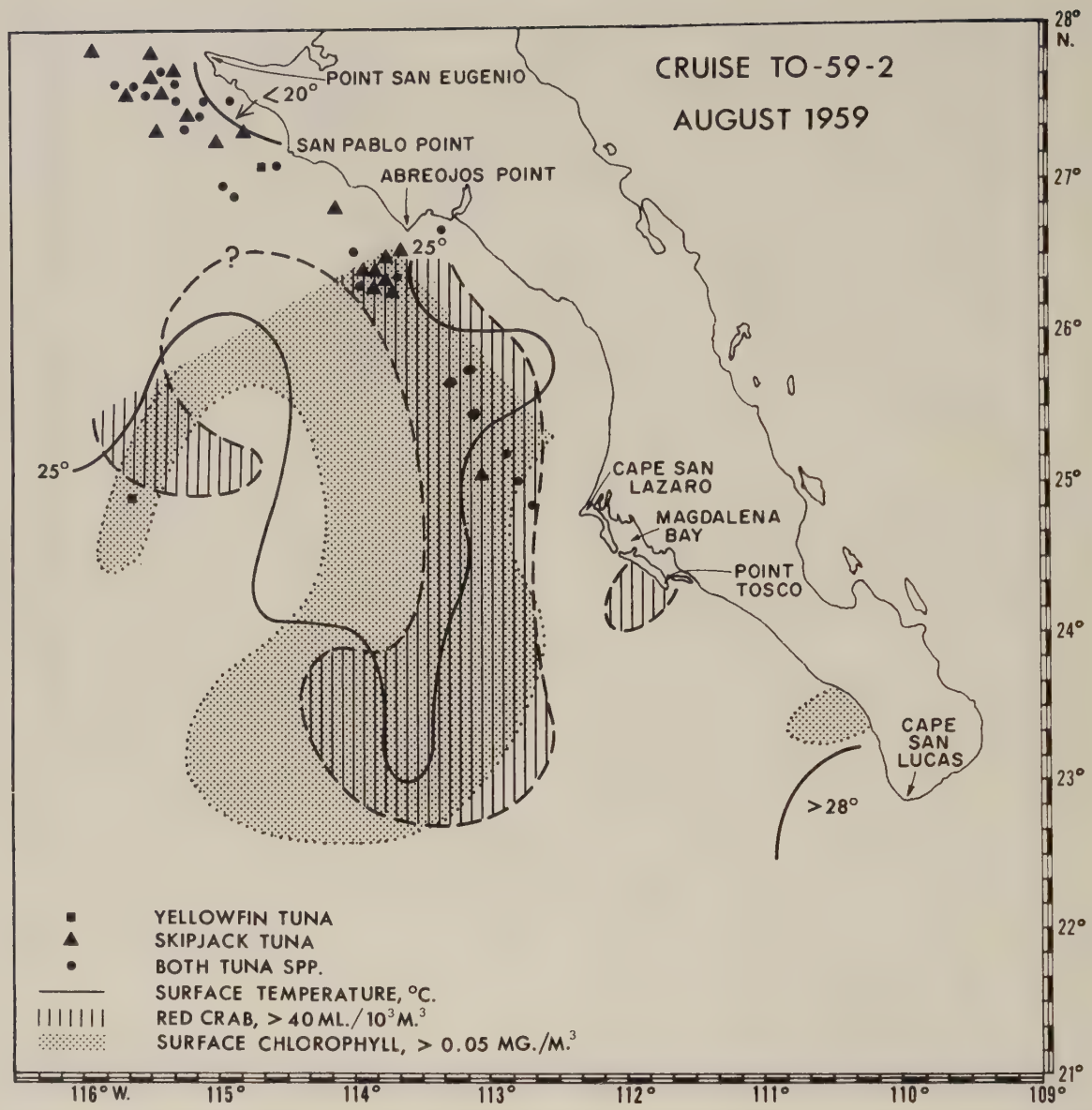

FIGURE 10.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO–59–2 and locations of contemporaneous tuna catches.

The area where red crabs were over 40 ml./1,000 m.³ shows the same close but not exact correspondence with the chlorophyll-rich area that was found on previous cruises, and all the tuna catches were made in or very close to this area. The highest concentrations of carnivores (tuna), herbivores (red crabs), and plants (chlorophyll *a*) all were in the same restricted area. Because all temperatures were suitable for tunas, the tunas occurred, as before, not only around but through the food-rich areas.

CRUISE TO–66–1

The cruise period in the area of interest was November 4–21, 1966. The cruise (figs. 13 and 14) included stations with numbers below 15 and above 70, which were occupied on behalf of another investigator and were all north of lat. 28° N.

As I expected, conditions were much more uniform throughout the area on this cruise than on any of the others, because coastal upwelling had ceased. The only inshore pocket of cool water,

TABLE 4.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10³ m.³ of water strained, on cruise TO–59–2*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10³ m.³			*Ml./10³ m.³*			*Ml./10³ m.³*
1	S	>40	20	S,Z	>40	36	Z	6
2	Z,M	>40	21	M	64	38	M,Z	34
5–6	H	2	21–22	H	36	38–39	H	2
6–7	H	4	22–23	H	20	40–41	H	93
7	Z	>40	26	Z	158	41–42	H	5
8	M	176	26–27	H	15	42	M	132
8–9	H	35	26–27	H	16	42–43	H	5
9–10	H	3	27–28	H	8	43–44	H	8
11–12	H	1	28–29	H	6	46–47	H	6
13	M	42	30–31	H	8	46–47	H	27
13–14	H	26	30–31	H	1,158	52	M	108
15	Z	6	31	Z	7	53	Z	128
15–16	H	2	32	Z,M	229	53–54	H	495
17–18	H	225	32–33	H	158	54	Z	9
18	Z	>40	33	Z	58	55	Z	8
18–19	H	24	34	Z	9	57	Z	15
19–20	H	43	35	Z	13	57–58	H	2
19–20	H	213	35–36	H	59	58	M,Z	20

which might have indicated upwelling, was a very small one off Point Tosco (21°–22° C.). Temperatures for the whole area were between 18° and 26° C. on part 1 of the cruise; on part 2, temperatures at reoccupied stations were only slightly (less than 1° C.) lower.

The range of chlorophyll *a* concentrations was about the same as on cruise TO–65–1, but their distribution was more uniform. Concentrations were over 0.1 mg./m.³ in most of the area as shown in figure 14. Concentrations were over 0.2 mg./m.³ at all stations north of lat. 26° 20′ N., and there only. Similarly, concentrations of red crabs were 40 ml./1,000 m.³ or higher in most parts of the cruise area (see table 6 for data). Finally, the recorded catches of tuna (all those for the period November 4–21) were scattered through the large area of suitable temperatures and abundant red crabs.

There was no opportunity to make a similar cruise closer to the end of the season for yellowfin and skipjack tunas off western Baja California, say in December or January. Such a cruise would probably have shown that the area available for the tunas had contracted because of the southward movement of isotherms, and a rather featureless distribution of the tunas—similar to that on cruise TO–66–1, associated with relatively uniform distributions of red crabs and chlorophyll *a*—in the area of suitable temperature.

OCEANIC PROPERTIES AND THE DISTRIBUTION OF TUNAS

The results of cruises TO–64–1, TO–64–2, 6608, and TO–59–2 all show the expected close agreement in detail between areas of relatively cool water that are attributable to upwelling and areas of relatively high surface chlorophyll *a*. The poor agreement between isograms of temperature and chlorophyll *a* in the northwestern portion of the cruise area shown in figure 6 is not necessarily an exception to the preceding statement, because the cool water may not represent upwelling there. The results of cruise TO–65–1 show a region of relatively high surface chlorophyll *a* in a locality and with a shape, which suggest an origin in upwelled water. No signs of upwelling appeared on cruise TO–66–1. The distributions of surface isotherms in space and time are consistent with previous information about upwelling off southern Baja California. Temperatures rise and chlorophyll *a* concentrations fall in the upwelling areas as the upwelling becomes weaker.

The results of all the cruises show rather close agreement in detail between the areas of relatively high surface chlorophyll *a* and the areas in which the concentration of red crabs is more than 40 ml./1,000 m³. The concentration of chlorophyll *a* which shows this agreement varies; on most of the cruises it was 0.2 or 0.1 mg./m³., but it was higher on cruise TO–64–1 and lower on cruise TO–59–2. The only complete lack of agreement appears in

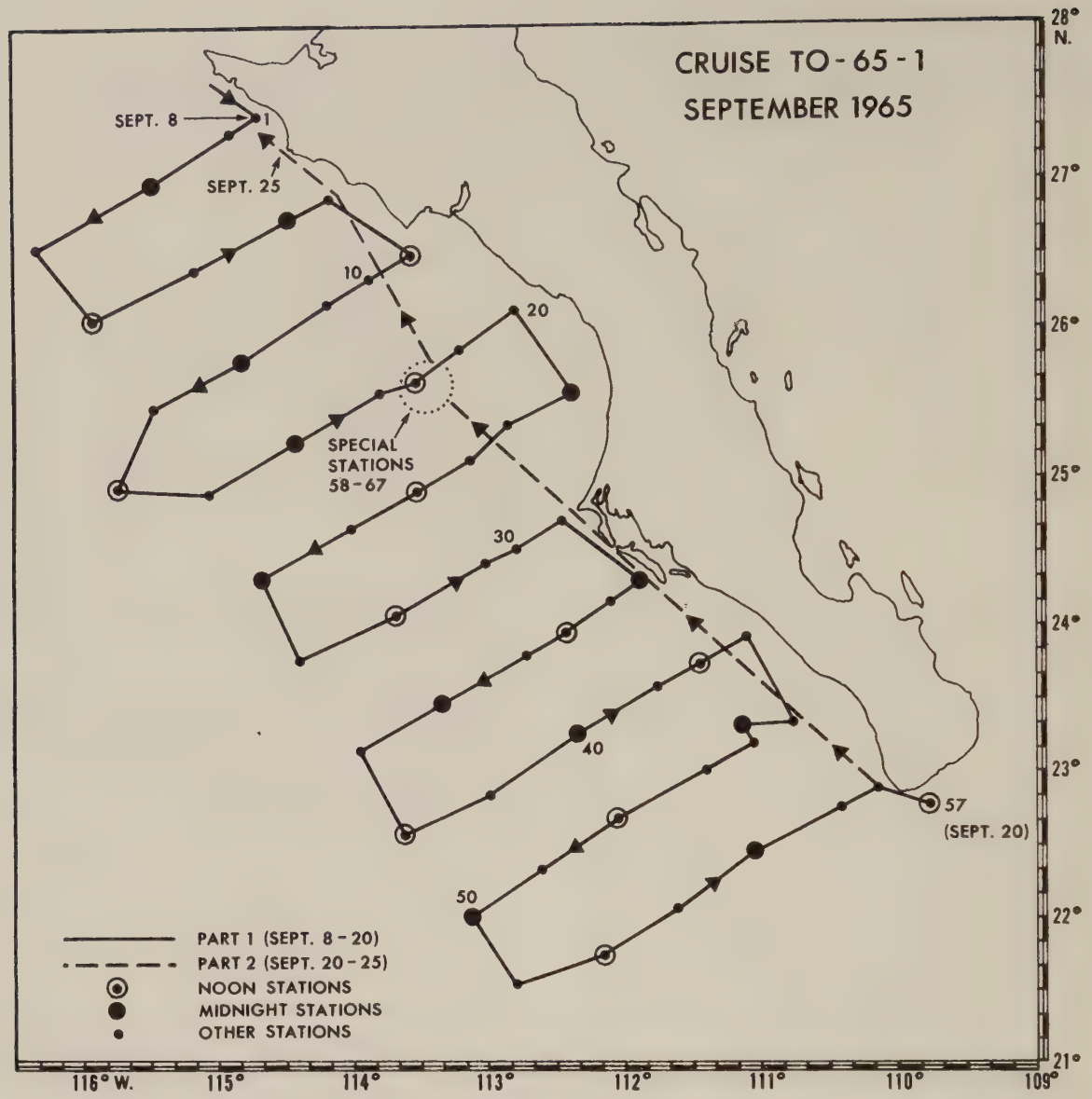

FIGURE 11.—Track and station positions for cruise TO-65-1.

the northwestern part of the cruise area shown in figure 6. Elsewhere in all the charts, agreement is fair to good. The area boundaries for the two properties seldom coincide, but they tend to lie close together and to have the same shape. Where the isograms of chlorophyll *a* follow those of temperature, all three properties—temperature, chlorophyll *a*, and red crabs—have a closely similar distribution (e.g., fig. 10).

The occurrence of red crab maxima with chlorophyll *a* maxima is not surprising because red crabs feed on phytoplankton, but the circumstances whereby they maintain aggregations in chlorophyll-rich areas are not altogether clear. On the one hand, the distribution data of Boyd (1967) and Longhurst (1967) indicate that the red crab can be swept away from the coast by the California Current during its pelagic phase. On the other hand, substantial numbers of this species occur in the benthos along the Continental Shelf and Slope (Boyd, 1967), and these individuals probably help to maintain pelagic concentrations in coastal areas by generating larvae and by ascending into the upper waters from time to time. Larvae are most

FIGURE 12.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO–65–1 and locations of contemporaneous tuna catches.

numerous in inshore waters off the west coast of southern Baja California before and during the upwelling season, and benthic adults probably produce many of them (Longhurst, 1968a). The maintenance of pelagic aggregations is probably served also by the formation of inshore eddies after June (Wyllie, 1966). I assume that these processes, together with the animal's own appreciable mobility, maintain high concentrations in inshore areas where food (phytoplankton) is abundant; when food is scarce inshore red crabs presumably sink, disperse, or die.

The presence of red crab concentrations in cool water on some of the cruises results from the relation between chlorophyll *a* and upwelling, and is, therefore, not apparent on cruises TO–65–1 and TO–66–1. Longhurst (1967) showed that red crabs are practically eurythermal between about 9° and 28° C.

The data on tuna occurrence are all consistent with the hypothesized association with surface temperature (about 20° C. or more) and food sup-

TABLE 5.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10³m.³ of water strained, on cruise TO–65–1*

[Lettersunder kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water; P, found in predator stomachs. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration
		Ml./10³ m.³
2	Z	64
3	M	1
6	Z	32
7	M	1
7–8	H	500
8	Z	6
10	S,Z	>40
11	Z	4
11–12	H	5
12	M,Z	3
12–13	H	5
12–13	H	20
15–16	H	5
16	M,Z	5
16–17	H	342
18	Z	2
20–21	H	18
21–22	H	9
22–23	H	15
26	M	22
29	S,Z	>40
36	Z	21
37	Z,M	12
39	Z	5
40	M,Z	4
41	Z	4
42	Z	6
44	Z	2
45	M	<1
49	Z	18
49–50	H	15
50	M,Z	24
51	Z	2
54	Z,M	3
(1)	P	>40
60	Z	5
61	Z	55
62	Z	3
63	Z	32
64	Z	3
65	Z	10
66–4	Z	2
(2)	M	>40
(3)	H	20
(3)	H	158
(3)	H	550
(3)	H	>40
(3)	H	2,500
(3)	H	100
(3)	H	30

[1] Stomach contents of 3 yellowfin tuna (*Thunnus albacares*) at Thetis Bank.
[2] Series of night surface hauls with the large micronekton net near Uncle Sam Bank.
[3] After station 67, on northbound track between lat. 25°50′ N. and 26°40′ N., at night.

ply (40 ml./1,000 m.³ or more of red crabs), for all cruises except TO–64–1. On that cruise the tunas showed a tolerance of temperatures down to 17° C., but no lower in the presence of a larger food supply than that available to them at or over 20° C. Only one small area of abundant food (over 40 ml./1,000 m.³) and no area in which it was highly abundant (over 100 ml./1,000 m.³) had temperatures at and over 20° C.; food was highly abundant only at temperatures below 17° C. This difficulty (for the tunas) did not arise on any of the other cruises. On cruise TO–64–2 the edges of the areas of abundant food were warm enough for the tunas, which were found there and nowhere else. On cruises TO–59–2, TO–65–1, and TO–66–1 all parts of the food-rich areas were warm enough for tunas, which were, accordingly, widespread in them; they might have been found in still other places in the food-rich areas if the fishermen had searched there. On cruise 6608 the situation was partly like cruise TO–64–2 and partly like the other cruises. Except on cruise TO–64–1, no tuna were ever found more than 20 nautical miles (37 km.) from the charted boundaries of the food-rich areas.

From these results I may conclude that yellowfin and skipjack tunas aggregate in the areas of most abundant food where surface temperatures are about 20° (±1°) C. or over in waters west of Baja California, except at the beginning of their seasonal entry into those waters when they may occur at temperatures down to 17° C. Temperature determines range limits (penetration northward and toward the coast), and food supply determines distribution within the range limits. Because the principal food in this area is the red crab which occurs in areas rich in phytoplankton, tunas generally aggregate in or near the areas of highest surface chlorophyll *a*, provided that temperatures are suitable.

Because the distributions of temperature, chlorophyll *a*, and red crabs are all partly controlled by the seasonal coastal upwelling, at least through September, the same is true of the distribution of the tunas. Concentrations of tuna prey are much higher off western Baja California than anywhere else in the eastern tropical Pacific, where they are generally less than 10 ml./1,000 m.³ (Blackburn, 1968). These high values are a consequence of the upwelling and of the unusually short tuna food chain. The upwelling, however, furnishes an environment that tends to be too cold for yellowfin and skipjack tunas in spite of its biological richness, and this physical feature is decisive. The tunas do not enter the area and exploit the rich food supply until temperatures begin to rise. They then aggregate around the edges of the large tongues or patches of food and gradually penetrate into the cores of those areas as they become warm. Later the distribution of both the food and the tunas

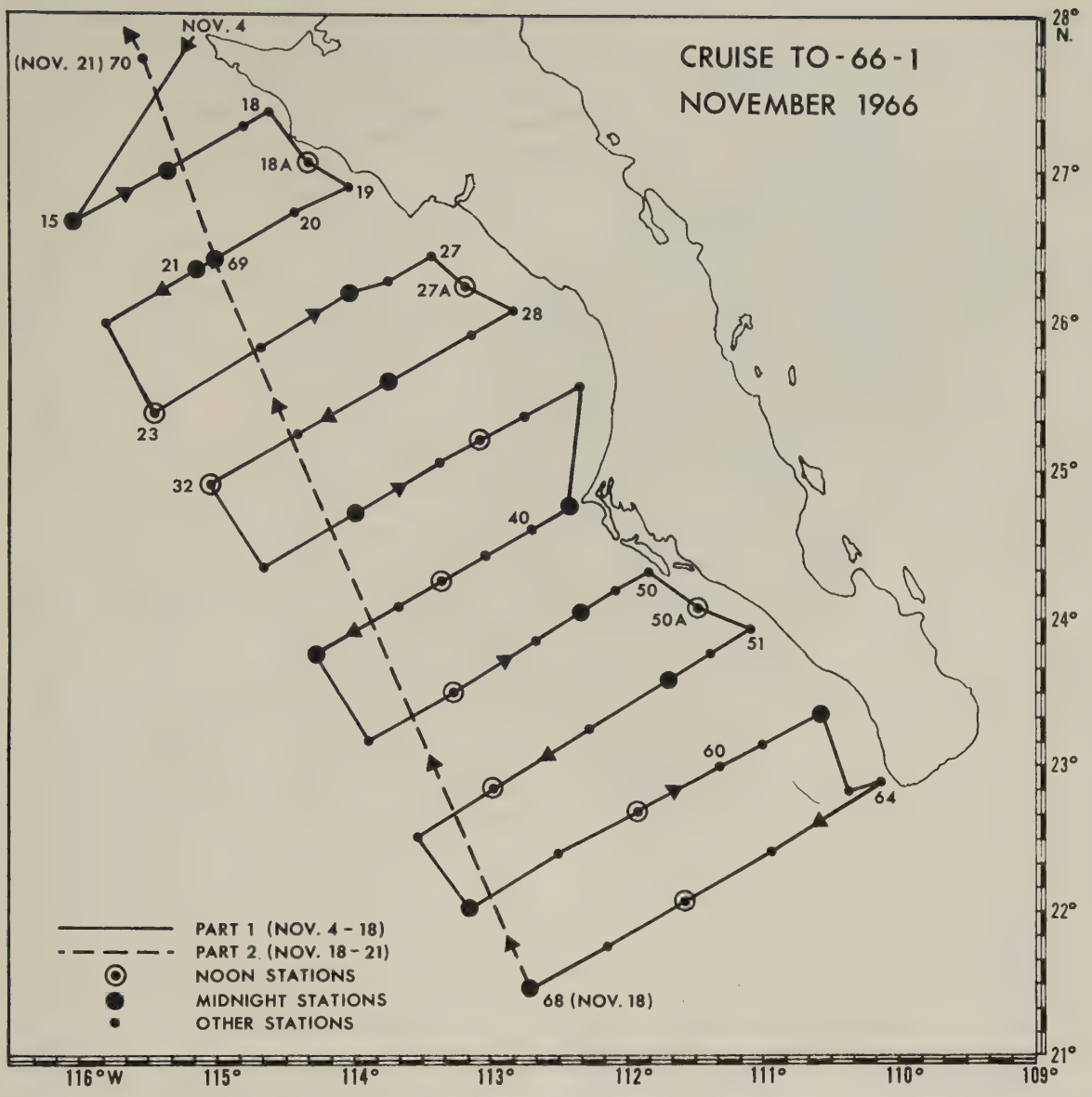

FIGURE 13.—Track and station positions for cruise TO–66–1.

becomes rather uniform in areas of suitable temperature, and finally the physical environment again becomes unsuitable with the start of winter cooling. The supply of pelagic red crabs remains fairly high throughout the year (Longhurst, 1967; Blackburn, 1968; and this paper).

The foregoing interpretation of the tuna distribution data might be criticized on two grounds. One is that nearly all the tuna catches shown in the charts were within 100 nautical miles (185 km.) of the coast, although suitable environmental conditions occurred much farther offshore on some of the cruises (see figs. 8 and 10), as well as in the inshore areas where the catches were made. Charts of IATTC data from the commercial fishery for many years, compiled by Joseph and Calkins (1969), show clearly that most of the fishing effort in the Baja California area is expended and most of the catch of both species taken within about 100 nautical miles of the coast. This situation is understandable because the tuna are associated with upwelling, which is a coastal process, and fishermen generally do not operate farther offshore than is necessary to make good catches. On

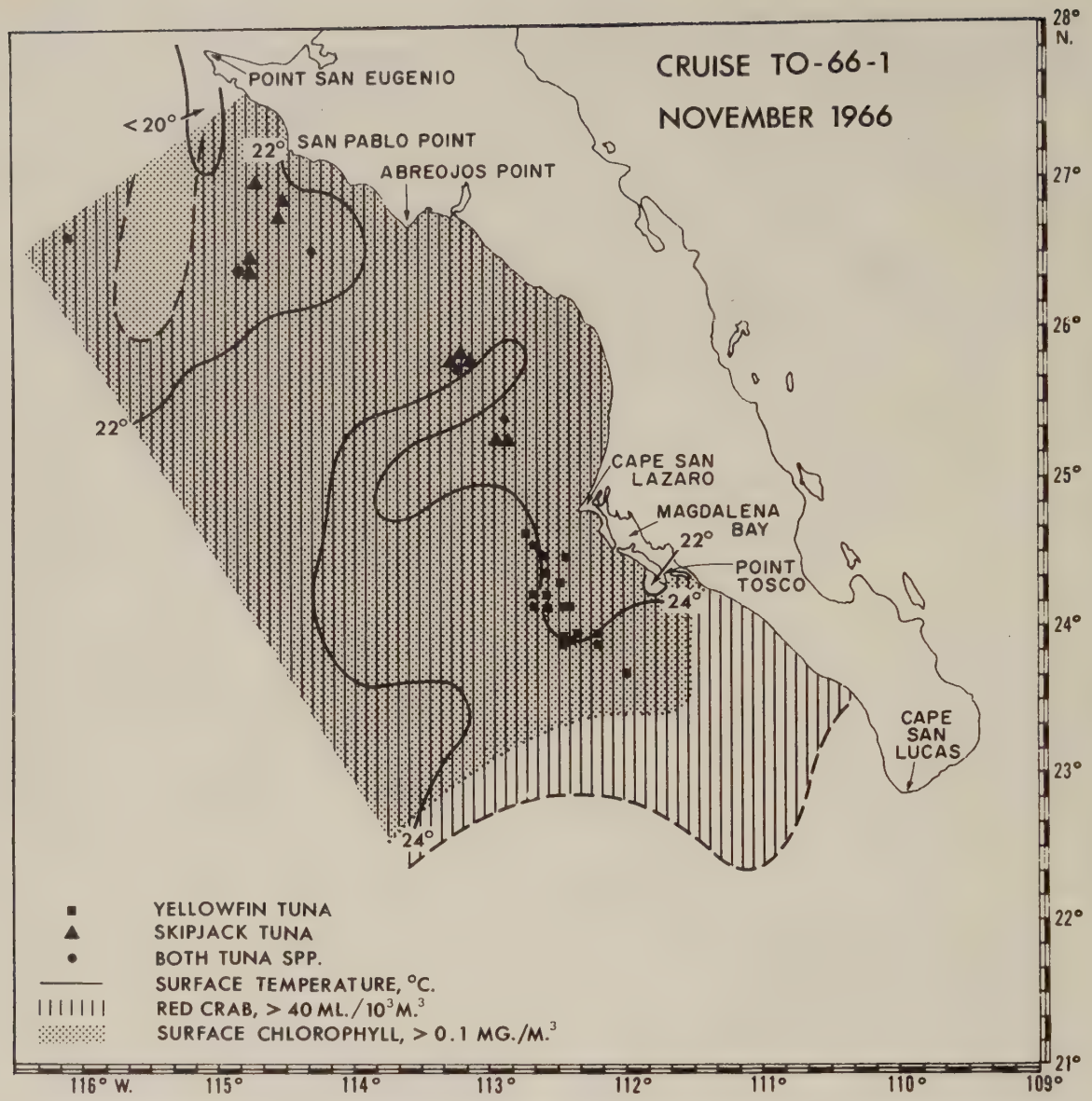

FIGURE 14.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO–66–1 and locations of contemporaneous catches.

the other hand, the IATTC charts show that yellowfin and skipjack tunas are sometimes sought and captured offshore, for instance at Alijos Rocks, about 150 nautical miles (278 km.) from the coast (fig. 2), and even about 1° of longitude to the west of that locality. Nothing suggests that these offshore tuna are not aggregated in food-rich areas of suitable temperature in the same way as the inshore tuna. Furthermore, one definite record of an offshore commercial tuna catch appears to be associated with a tongue of food-rich water (fig. 10). This catch was at Alijos Rocks on cruise TO–59–2. The only other cruise in the present series which yielded information about properties at Alijos Rocks was TO–65–1 (see fig. 11, station 14). On that occasion, no tongue of biologically rich water reached the Rocks area, concentrations of chlorophyll *a* and red crabs were low, no tuna were seen or caught while the scientific party was fishing at the Rocks, and no commercial catches were recorded there during the cruise period.

The other possible objection to the model of

TABLE 6.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10³m.³ of water strained, on cruise TO–66–1*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10³ m.³			*Ml./10³ m.³*			*Ml./10³ m.³*
15	S	>40	33–34	H	5,238	50	S,Z	>40
16	M	<1	34	S,Z,M	>40	52–53	H	43
17	Z	6	34–35	H	720	53	S, Z,M	>40
18A	Z	12	35	Z	7	53–54	H	25
20	S,Z	>40	36	Z	35	53–54	H	87
20–21	H	23	37	Z	7	56	Z	>40
21	S,Z,M	>40	38–39	H	20	57	M	<1
21–22	H	2	39	Z	41	59	Z	7
23–24	S	>40	39–40	H	13	60	S	>40
24	Z	7	40	M,Z	67	61	Z	57
24–25	H	20	41	Z	7	62	Z	50
25	M,Z	>40	42	Z	7	63	Z	7
25–26	H	53	43	S,Z	>40	65	S	>40
26	Z	27	43–44	H	73	68	Z	>40
27	Z	18	44	Z,M	19	(1)	H	233
29	Z	26	45	S,Z	>40	(1)	H	70
29–30	H	37	46	Z	13	(1)	H	150
30	S,Z,M	>40	47	Z,S	>40	(1)	H	82
30–31	H	704	48	M,Z	144	69	S,Z	>40
30–31	H	792	48–49	H	87	(2)	H	>40
33	S,Z	>40	49	Z	205			
33–34	H	>40	49–50	H	260			

[1] After station 68, on northbound track between lat. 23°40′ N. and 25°30′ N., at night.
[2] Immediately after station 69, on northbound track, at night.

tuna distribution offered in this paper is that many people who are acquainted with the Baja California fishery consider that yellowfin and skipjack tunas are distributed in relation to the banks shown in figure 2 and that abundance is higher at the banks than elsewhere, except when temperatures are low. No publications clearly demonstrate this relation as far as Baja California is concerned, and no studies off Baja California or elsewhere show conclusively the nature of any "bank effect" which might be attractive to tunas. In fact, only one such study has been attempted and the results were inconclusive (Bennett and Schaefer, 1960, at Shimada Bank in the eastern tropical Pacific). Nevertheless, belief in some kind of favorable bank effect upon tunas is so widespread that it must be considered here.

The tuna catches charted in figures 4, 6, 8, 10, 12, and 14 may be compared with the bank positions in figure 2. Many of the catches were made at or very near banks; they can be classified into two groups. All of those for the periods of cruises TO–64–2, 6608, TO–59–2, and TO–65–1 were in or close to tongues or patches of upwelled water, which either enveloped or touched the banks. None of the catches in the periods of cruises TO–64–1 and TO–66–1 were associated with upwelled water. On TO–64–1 no such water was warm enough for the tunas to enter, and on TO–66–1 there was none at all. The charts show also that many catches were in areas of upwelled water which were not close to banks, except on cruises TO–64–1 and TO–66–1.

When upwelled water of coastal origin extends over banks, it provides a ready explanation not only for the catches of tuna on banks (and at Alijos Rocks, as noted above) but also for the catches made between the banks. The unspecified bank effect may exist independently of the upwelling effect, but it is not required to explain the tuna distributions. If a bank effect exists, it is probably small in relation to the upwelling effect, and the banks are probably more suitable for tuna when upwelled water reaches them (providing it is not too cold) than when it does not. An observation from Uncle Sam Bank, which is very frequently visited by fishermen during the tuna season, is pertinent. Surface temperature charts for CalCOFI cruises 6007–8 (July 26 to Aug. 13, 1960, in the area of interest) and 6008 (Aug. 20–22, 1960) both show tongues of cool water (but over 20° C.) protruding offshore from the northern upwelling area. On the earlier cruise the tongue lay considerably west of Uncle Sam Bank, but on the later cruise it had changed its position and enveloped the bank (Scripps Institution of Oceanography, 1962a, 1962b). No tuna catches were recorded near the bank during the first cruise period.

but some were recorded there during the second period.

On the other hand, tuna aggregations upon banks which are not affected by upwelled water might be primarily attributable to a bank effect. Further work is needed to establish the reality of the bank effect and to explain it if it does exist. Obviously, this research should be attempted in a situation where upwelling is not likely to interfere with the bank environment, such as one of the offshore southern banks toward the end of the tuna season. In the meantime, it is reasonable to assume that some feature of banks makes them slightly more attractive to tunas than other areas when temperatures are suitable, and that this feature affects tuna distributions in situations where upwelled water does not interfere. Off Baja California these situations are probably most common in the southern part of the area, where upwelled water does not seem to reach far offshore; at the beginning of a tuna season when tuna are unable to enter upwelled water; and after all upwelling has ceased.

Fishermen often make an additional observation that tunas aggregate near boundaries between blue and green water. Some of the results of this study, especially for cruise TO–64–2, are consistent with that opinion. Blue water would frequently have suitable temperature but not much food; green water may contain suitable food but be too cold. Tuna would be expected to aggregate at the boundary under those circumstances.

The relation of tuna to the Cape San Lucas front was discussed under cruise TO–64–1. Evidence is lacking that this particular front has any effect upon tunas independent of the tuna-limiting temperatures that may occur in it. Low temperature tends to be limiting, whether located in the front or not, and no other feature of the front seems to have any effect upon the tunas.

If the area west of Baja California could be thoroughly and frequently monitored for surface temperature and surface chlorophyll *a* during a tuna season, it would be possible to specify areas in which aggregations of yellowfin and skipjack tunas would be expected—including offshore areas which fishermen might not otherwise visit—and those in which tuna would not be expected. This work could perhaps be done from ships, which already yield much data on surface temperature and could be equipped to yield data on surface chlorophyll *a* (Lorenzen, 1966). The chlorophyll equipment would be costly, however (about $2,000 per ship), and require careful maintenance aboard ship. Overflying aircraft or satellites offer another possibility. They would probably yield much more useful data than ships except in cloudy situations. Methods of measuring surface temperature from sensors above the ocean already exist, and measurement of surface chlorophyll is said to be feasible (Duntley, 1965). Obviously, the chlorophyll information could assist in mapping distributions of other useful organisms besides tuna—for example, the red crab itself, a possible human resource (Longhurst, 1968b), and other herbivores. Temperature data alone would be insufficient to specify distributions of tuna or red crab.

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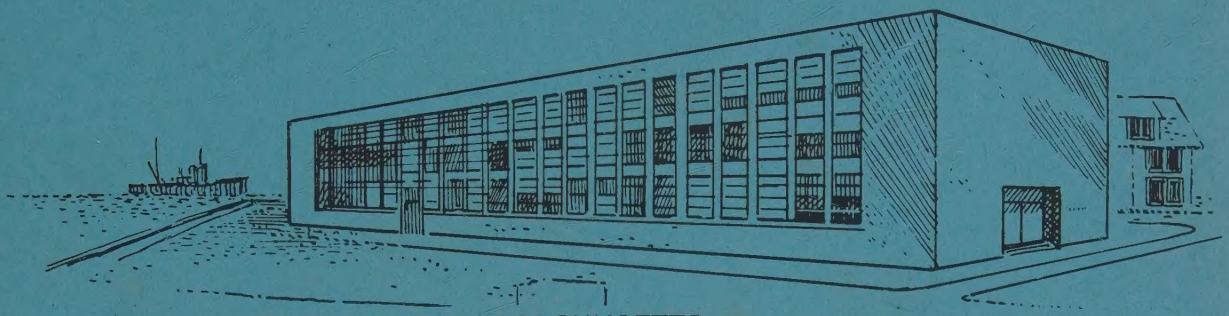

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